Future Optical Communications Systems

An OIDA Forum Report

June 2008

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Foreword

The communication equipment industry has survived the bubble and returned to health. Video is an important revenue generating platform for both cable and telecom service providers and will also impact heavily on the traffic management issue. The near term needs can be met by improving the performance of the present set of optoelectronics devices such as distributed feedback (DFB) laser arrays, tunable lasers, fast and complex modulators, arrayed waveguide gratings (AWG), and reconfigurable optical add drop multiplexers (ROADM). The use of electronic and optical compensation techniques and new signal encoding formats have extended the reach of directly modulated lasers. Low-cost optical-electrical-optical (OEO) conversions allow an alternate approach to network evolution. Coherent transmission eliminates signal impairments but presents multiple challenges. In the fiber to the home/curb environment, the potential for truly photonic integrated circuits to reduce assembly costs and simplify functionality is slowly becoming a reality. 100 Gb/s transport in the core is achievable to accommodate the Internet growth forecast in the short-term. However, there is no such optoelectronics device base for a terabit/s network (which we now refer to as 'terabit photonics'). We need to advocate the initiation of comprehensive R&D efforts to generate new device and system concepts over the next decade. In fact, we now expect the demand for high speed bandwidth to exceed our capacity significantly over the next decade. This implies that network-choking will be an ongoing problem similar to 'traffic jams' in major cities today.

In addition, components suppliers need to furnish devices and/or modules with high performances and more functions at low cost to meet future requirements. This may mean that some device/module manufacturers will turn to the consumer market for volume scaling. The threat of display-choking (communicating in and out of the display with a remote processor) is emerging on the radar screens of many television manufacturers as they progress towards high-definition television (HDTV). By providing the consumer with an active cable solution with embedded optics, it may be possible to reduce 10 Gbps technology cost through volume production to ease the issues of display-choking.

The conclusion of this forum is to pursue photonics integration. Only viable photonics integration processes can achieve this goal and keep up with future needs of communication systems beyond terabit/s. We must promote the adoption of viable integration processes to sustain progress. We also believe that photonics integration will positively impact the volume consumer market for interconnects in addition to the network edge.

With special thanks to Fred Leonberger, our forum facilitator, for the stellar group of presenters and panelists he brought together for this two-day forum and for his contributions to this report. With thanks also to Bill Ring for his valuable input to the report.

Michael Lebby
OIDA President and CEO

Table of Contents

Table of Figures

Tables

1 Executive Summary

1.1 Business Issues

Global telecommunications revenue approached $3 trillion in 2006, a growth of 11.2% over 2005. In 2006, the international segment achieved over $2 trillion for the first time, while the United States segment achieved $945 billion. In the transport services market, wireless continues to grow over landline, a trend which is expected to continue. Capital expenditure as a percentage of revenue for U.S. wireless and wire-line telecom service providers has stabilized at about 16%.

The communication equipment industry has survived the bubble and returned to health. The combined revenue of supplies of communications equipment reached about $150 billion in 2006. The global market for optical transceivers will grow from about $823 mission in 2006 to about $1.5 billion in 2011. Fiber optic revenue took a strong dip in the post-bubble years (2001-2003) but has now grown significantly into a strong, consistent business. Revenue for 2006 topped $10 billion, growing 9.5% over 2005.

The number of North American fiber to the x (FTTx) connections grew from about 112,000 in June 2004 to over 2 million as of October 2007. AT&T is investing $4.6 billion to roll out FTTx services to 19 million U.S. homes by 2008. Verizon is spending $18 billion to reach 18 million homes by 2010.

1.2 Core, Metro, and Access Technology

Demand for bandwidth by consumers and business is continuously increasing. Telecom network carriers are deploying new services and moving into the entertainment and media delivery space. Connectivity, mobility, video, file sharing, peer-to-peer applications, online gaming, security, and networked data backup are pushing new requirements into the telecom operator environment. The amount of data traversing networks is currently growing around 75% year-on-year.

The network has three key segments: the core, the metro, and access. Multiple networks interoperate, including private line, leased line, and enterprise and web server connections. Both cable and telecom operators sell bandwidth and private lines, in addition to supporting the public network. Each segment of the network levels relies on the key technologies of optical, electrical or RF signaling, transport, and connection. The primary protocol of choice for current networks is the Internet protocol (IP).

In the core of the network, long distance routes require high bandwidth capacity as the access points load the network with more transport information. Interoperability and hand-off are important features for telecom networks. Transport over the network typically occurs via the optical transport network (OTN, or G709). A large amount of synchronous optical networking/synchronous digital hierarchy (SONET/SDH) legacy equipment remains in operation.

The Metro Ethernet Forum (MEF), initiated in June 2001, has worked on scalability and other issues to enable Ethernet to move into the provider network. Today, “carrier-grade” Ethernet is expanding into the service provider backbone. Flexible and reconfigurable metro networks are being almost universally deployed, due to attractive features such as remote provisioning and overall lower operating and upgrade costs.

The access network is a bottleneck. Currently only about 2% of U.S. subscribers and 13.4% of enterprise customer buildings in the United States connect with fiber. Ethernet access deployment is increasing in the business environment.

1.2.1 Residential Broadband and FTTx

The consumer connection is the current high-growth area for access nodes. The majority of households connect by wire line (cable or digital subscriber line). Within the U.S., the cable modem is the most common connection. We expect that consumer bandwidth requirements will continue to increase at a minimum rate of 30% per year.

The number of fiber to the home (FTTH) subscribers worldwide exceeded 10 million in early 2006. In 2009, passive optical networks (PON) will have 28.9 million subscribers and Ethernet point to point (EP2P) will have 2.3 million. The number of connections is growing fastest in Asia. Both South Korea and Japan have aggressive fiber to the home connection projects. Within South Korea, the government is pushing to connect 100% of households to the network by fiber.

1.3 The Impact of Future Video Traffic on the Network

Video is an important revenue-generating platform for both cable and telecom operators. Revenue from the video content will surpass voice and internet revenue streams. Current forecasts for video data show tremendous growth over the next few years. Video streaming (personal and business) will dominate over other content and communication data, and will exert a large impact on bandwidth requirements.

The movement toward high-definition television, internet television (IPTV), and video-on-demand requires greater bandwidth and poses new challenges. The network must deliver video content from multiple sources over a common infrastructure while ensuring quality of service (QoS). Telecom carriers are considering various architectures for delivery of the video content. Several architectures assume caching of video on local metropolitan servers.

The key concern with current forecast of video on demand (VOD) service for consumers is the impact on the traffic management of the carrier networks. Video on demand service requires bi-directional transmission. VOD traffic is user dependent, highly asymmetric, and subject to cycles of peak demand. As telecom operators enter the video space to offer triple play packages over their networks, changes are occurring in the network structure. Telecom operators are offering internet service over the phone lines–DSL and asymmetric DSL (ADSL). They transmit video content via either DSL or passive optical network architecture such as Verizon’s FiOS (Fiber Optic Services). Outside the United States,

where fiber to the home networks have been installed more rapidly, the PON architecture is more prevalent. Successful deployment of IPTV and video services will require skillful management of network resources.

1.4 Prospects and Issues for Fiber Optic Networks

Global internet traffic has increased at a rate of 75% per year for the past five years. Video now accounts for nearly 30% of all internet traffic and will account for 60% within a few years. These changes have driven widespread deployment of 10 Gb/s links. The industry is installing new network upgrades to 40 Gb/s in the core. The timing and level of deployment of 40 Gb/s systems depends strongly on the pricing relative to 10 Gb/s core network utilization and capacity planning. Carriers are asking for 100 Gb/s transport in the core to accommodate the growth forecasts. Installations of carrier Ethernet in the metro networks have been increasing rapidly.

Increases in data and flat or reduced cost of services have created an increasing burden for network operators. The access bandwidth available to users has grown at 30% per year. Verizon has been rolling out fiber to more than 40,000 homes per month.

Some contenders view the all-optical network as inefficient due to concerns such as:

- Wavelength congestion
- No sub wavelength grooming
- Service limited by number of wavelengths
- Agility and service provisioning

An alternate approach to network evolution is to enable low-cost optical-electrical-optical (OEO) conversions and bandwidth virtualization across the network. The concept is straightforward: manage the bandwidth of the network in one control plane and the wavelength transport in another plane.

It is possible to eliminate impairments in signal transmission by encoding the transmitted signal and recovering the phase, polarization, and amplitude with a local oscillator and electronic processing. To achieve coherent detection, we must know the phase, frequency, polarization and amplitude of the signal. Coherent communication presents multiple challenges but promises potentially large rewards. At both 40 Gb/s and 100 Gb/s, coherent transmission allows longer transmission distances (6000 km and 2000 km) and high tolerance to both chromatic dispersion (CD) and polarization mode dispersion (PMD).

1.5 Components for Core / Metro

Today’s networks make widespread use of tunable lasers externally modulated at 10 Gbps and of reconfigurable optical add-drop multiplexers (ROADM) with wavelength selective switches for add/drop functionality. These new components enable more flexible and remotely reconfigurable networks that provide enhanced value to service providers.

In the coming years, we expect to see less expensive 40 Gb/s sources, smaller transceivers, and more complex ROADMs.

Companies that previously supplied only components are introducing higher-level products, such as optical nodes that incorporate amplification, signal monitoring and dispersion management, all under common software and firmware control.

Electronic and optical compensation techniques and new signal encoding formats have extended the reach of directly modulated lasers (to >100 km at 10 Gb/s) and will allow the adoption of 40 Gb/s transmission on systems designed for 10 Gb/s. These compensation and encoding techniques will continue to evolve rapidly and will speed the adoption of new relatively low-cost transmission systems.

The high interest in 100 Gb/s data transmission is also fueling significant innovation. Component suppliers are developing several parallel approaches such as 10 x 10 Gb/s and 4 x 25 Gb/s as well as 100 Gb/s serial transport technology. The success of 40 Gb/s will depend on the rate at which industry can supply 100 Gb/s components and develop 100 Gb/s standards.

Progress in optical fiber can affect network design and cost structures. While fiber fabrication is a mature technology, any reductions in loss or dispersion can enable new network build outs which would be future proof as technology develops. Progress in photonic crystal fiber could lead to all-fiber devices (e.g., compensators) and, over the long term, to ultra-low-loss fiber.

Carriers have responded to the growing demand for bandwidth by deploying 40 Gb/s long-haul and ultra-long-haul line cards and transport systems. To achieve 40 Gb/s transport on the current core network, the systems must be able to transport the information over distances of 1000 to 3000 km without excess degradation of the signal-to-noise ratio or bit error rate. The 40 Gb/s transport line card systems will evolve toward lower size, weight, and cost.

Optical amplifier technology has replaced electrical repeater systems in the core network, thereby reducing power requirements and complexity. In erbium doped fiber amplifiers (EDFA), a 1480-nm or 980-nm source pumps erbium fiber to amplify a 1550-nm transport signal. Erbium amplifiers are discrete modules placed at discrete locations within the network. In long-haul systems, telecom carriers are making a transition from discrete amplification to distributed Raman amplification. In recent years, carriers have been moving to Raman amplifiers for ultra-long-haul systems and for undersea networks. In undersea networks, Raman amplification makes it possible to eliminate discrete repeaters and to reduce or eliminate power suppliers along the fiber length.

The key concerns with high-bit-rate, long-distance systems are polarization mode dispersion, chromatic dispersion, and electronic circuit capability. New modulation formats can reduce the impact of PMD and CD at signaling rates above 10 Gb/s second for single-wavelength sources. By optimizing the modulation format, it is possible to render the

transmission signal more tolerant to the PMD of the installed fiber base and thereby achieve longer link distances without laying new fiber.

In new photonic band gap fiber, the light is no longer guided by total internal reflection. The air gap reduces non-linear refractive index issues and allows higher power transmission in the core of the fiber. This development can potentially allow the use of high power amplifiers. It also increases the spectral efficiency of the fiber.

It is difficult to operate dense wavelength division multiplexing (DWDM) systems with uncooled lasers because of the requirement for wavelength stability. However, several companies are developing technology to move away from coolers to quasi-cooled or uncooled operation. The most common quantum well laser in production is built from the InGaAsP system because sudden failures can occur in material which contains aluminum. However, InGaAlAs/InP devices can achieve better performance than InGaAsP devices because of the improvement in conduction band offset.

Transceiver packages continue to shrink. The Xenpak and Xpak modules used 2.5 Gb/s input electrical interfaces, while the XFP and SFP+ accept 10Gb/s line rates directly into the transceiver. Transceivers in smaller packages draw less power because the designers removed electronic circuits from the module. The market has driven substantial erosion of average selling prices for high-volume, mature products such as shortwave transceivers. The price erosion has created a challenging environment for optical transceiver companies that must generate enough margin to stay afloat and also to fuel research on next-generation products such as 40 G and 100 G. To meet the challenging price requirements, some vendors have developed a vertical integration strategy. This strategy can succeed only with high sales volumes.

1.6 Components for Metro / Access – FTTx

Transceivers and transponders are key components in metro, access, and enterprise systems. These devices range from high performance large 300-pin transponders to small pluggable XFP and SFP transceivers for datacom applications. This class of devices has trended toward ever-lower power consumption, size, and cost. Devices at 1 Gb/s are in mass deployment. Most switch and server ports today run at 1 Gb/s.

Since the introduction of coarse wavelength division multiplexer (CWDM) at 10 Gb/s and recently long reach multimode (LRM) 10 Gb/s optics, the switch to 10 Gb/s port has been increasing dramatically. The increase in core bandwidth demands and the amount of IP traffic crossing networks, switches, and routers are driving the adoption of 10 Gb/s. With the core networks becoming congested and metropolitan switch ports aggregating 10 Gb/s, the deployment of 40 Gb/s serial solutions has been increasing.

One of the key concerns for FTTx deployment is fiber management. With SMF28e single mode fiber, sharp turns in the conduit can cause bend loss at the turn or potentially crack the fiber and cause a break. To prevent this effect on FTTx deployment, Corning has generated a new fiber cladding called nano-structured fiber.

For advanced data communication, the package in development at 10 Gb/s is the SFP+ module. This module removes several of the electronic functions currently found in the XFP transceiver and transponder. The overall impact on the switch or blade is to reduce power dissipation and to increase port count on the line cards.

In the FTTx arena, there is a movement to gigabit passive optical networks (GPON). This trend is placing significant pricing pressure and volume requirements on DFB lasers and avalanche photodiodes (APD) to meet the system and power-budget specifications mandated by the International Telecommunications Union. The alternative to GPON is gigabit Ethernet PON (GEPON), which is standardized by the Institute of Electrical and Electronic Engineers (IEEE). In the case of 2.5 Gb/s APDs, projected volumes are at least an order of magnitude larger than historically needed for traditional telecom applications. Meanwhile, for next-generation GPON, there could be a requirement for amplification requiring high performance low-cost semiconductor optical amplifiers (SOA) at both 1490 and 1310 nm.

1.7 Photonic Integration

At the component level, a key issue is the rate of progress in photonic integrated circuits (PIC) versus optical-hybrid approaches to provide the functionality needed in future components and systems. For monolithically integrated solutions to be commercially successful, the technology must deliver superior performance and reliability at acceptable prices and performance. Telecom networks have successfully deployed integrated devices such as arrayed waveguide gratings (AWG), reconfigurable optical add drop multiplexers (ROADM), distributed feedback (DFB) laser arrays, tunable lasers, and 10Gb/s modulators including complex modulators (e.g., DQPSK and duo binary modulators). Commercial deployment of integrated devices with ten laser arrays has been achieved. For passive optical networks, several companies have been developing photonic integrated circuits to replace the transistor outline (TO)-can triplexer module deployed in FTTH systems.

Several companies believe successful integration can only be achieved by a hybrid integration approach, such as fabricating a silicon platform (for example, a silicon or silica waveguide device) and die bonding InP devices (sub-components) to the platform. It is possible to develop complex transmitter and receiver assemblies by the hybrid integration approach. In this example, the yield curve is too steep to fabricate complex DFB arrays. Some level of hybrid integration would allow better cost and performance than discrete devices. But beyond some threshold of complexity, discrete devices would be more profitable.

The essence of the silicon photonic integrated circuit approach is to fabricate both optical and electrical elements by complementary metal oxide semiconductor (CMOS) wafer processing. Several research groups are investigating silicon light emission. One approach is to grow or implant erbium crystals in the silicon. Another approach is to exploit quantum size effects (silicon/silicon dioxide nanoparticles) to generate gain and hence light within the crystal. In yet another approach, III-V material is wafer bonded to a silicon resonator to provide the light source or photon generator. The silicon waveguide acts

as the laser resonator circuit and provides the feedback mechanism to the photon generator to enable gain and hence lasing action. The principal issue with the wafer bonding process for silicon CMOS devices is the introduction of the III-V material into the fabrication facility or process line.

The alternative to the silicon CMOS photonic integration approach is the “pure” InP integration. This wafer process technology begins with an InP substrate rather than a Si substrate. Flip chip bond pads or wire bonds connect the InP chips to the electrical drivers. Silicon-based electrical circuits (CMOS, SiGe) supply the electrical functions to drive the InP integrated device. One of the key issues with InP integration is yield. The advantage of the InP optoelectronic integrated circuit is the light source. The laser can be integrated into the circuit at the base wafer epitaxial growth stage. This approach makes it possible to fold most of the routing and detection emission functions into the first wafer processing stage. Indeed, this enabled the initiation of commercial deployment (see first paragraph in this Section).

2 Business Issues

There are many metrics by which to monitor the health of the optical communications market and to forecast future growth rates and dynamics. The telecom bubble and subsequent bust was characterized by an inordinate increase in capital spending on the part of the carriers (as a percentage of their revenue) as they put in place what now seems like, for that time, excessive capacity for forecasted internet growth. A reduction to more historical norms in capital expenditures (CAPEX) and an associated attention to reducing operating expenses (OPEX), as well as major mergers, brought the carriers back to better financial health from which they could grow in the coming decade. Mergers are beginning to occur among the major original equipments manufacturers (OEM) which will bring synergies and economies of scale to sustain financially healthy and innovative equipment suppliers.

Will similar consolidation occur at the component/module level? Will the recent string of successful acquisitions and some IPOs continue? A key question is what will be the state of the component company landscape in five years and how will that effect the rate of new product innovation? A closely related question is whether the venture community will continue to invest, at what level, in optical communication businesses.

2.1 Telecom Financial Picture

Global telecommunications revenue approached $3 trillion in 2006, a growth of 11.2% over 2005, as highlighted in Figure 1.

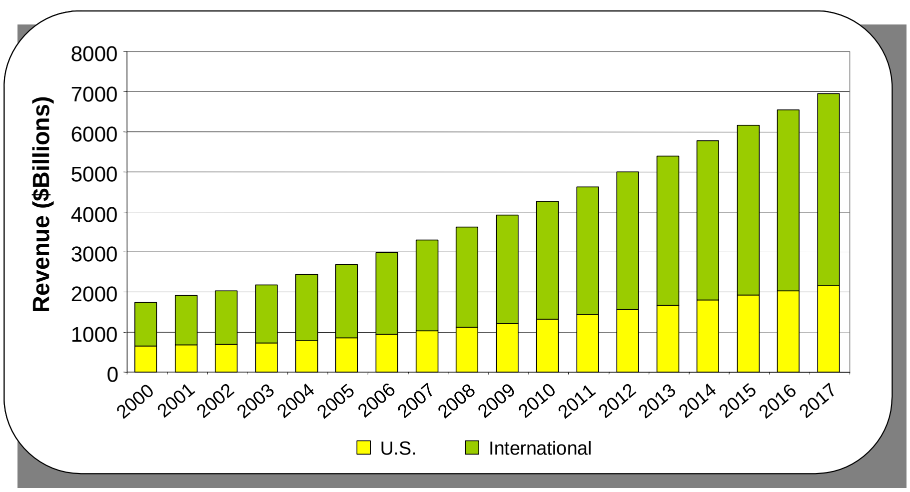


Figure 1: Global Telecommunications Revenue and Forecast, 2000-2017

Sources: TIA, OIDA, OIDA members

In 2006, the international segment achieved over $2 trillion for the first time, while the U.S. segment achieved $945 billion. The international industry is composed of the following regions: Canada, Europe, Middle East (ME) and Africa, Latin America, and Asia and Pacific (AsiaPac). The growth in the U.S. was led in 2006 by strong growth in a

number of technological areas that included wireless devices, network equipment, and wireless services that supported new growth areas such as internet access. The growth in the international industry was fueled mainly by strong growth in wireless transport and internet access. The total industry revenue is expected to climb consistently to nearly $7 trillion in 2017, with growth rates in the 8-10% range.

The regional segmentation of the telecommunications industry, including the U.S., is presented in Figure 2. Revenue breakdown shows that Europe had the largest share of the telecommunications revenue in 2006 and exceeded the U.S. industry by approximately $65 billion (U.S. revenue of $945 billion versus Europe revenue of $1.01 trillion). Five years ago, the U.S. telecommunications industry led the regional revenue over Europe. It lost its leadership in 2002, in an era when the U.S. was achieving growth rates of only 1-2% while Europe had growth rates of 7-8%. The low growth rates in the U.S. were in part due to the aftermath of the bubble period in 1999-2000. The U.S. growth rates have now rebounded to the 8-10% range and look set to achieve a 2007-2017 compound annual growth rate (CAGR) of 7.8%. Over the next decade, the Asia Pacific region is forecast to grow strongly and become the third largest player in the telecommunications industry, with a 2007-2017 CAGR of 10.5% and revenue approaching $2.2 trillion in 2017, the highest in the marketplace.

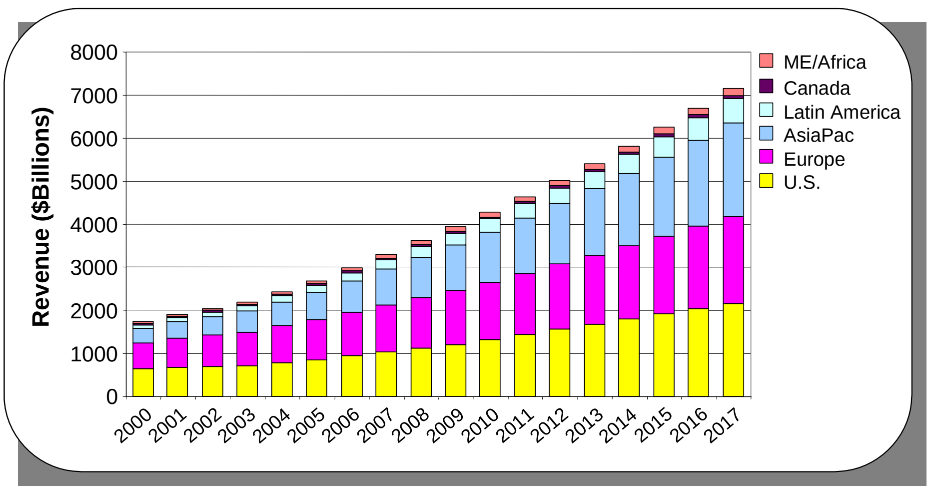


Figure 2: Global Telecommunications Revenue and Forecast by Region, 2000-2017

Sources: TIA, OIDA, OIDA members

As shown in Figure 3, fiber optic revenue took a strong dip in the post-bubble years (2001-2003) but has now grown significantly into a strong, consistent business. Revenue for 2006 topped $10 billion, growing 9.5% over 2005. The primary reason for this growth was the recent reinvestment of fiber by both regional Bell operating companies (RBOC) as well as local municipalities. Both industry segments are pushing hard to have fiber penetrate deeper into the network in order to support improved broadband offerings.

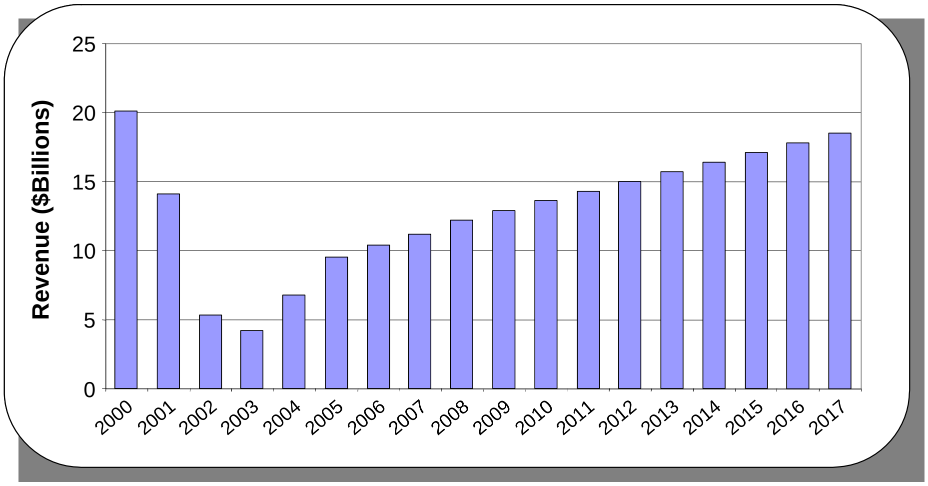


Figure 3: Fiber Revenue and Forecast in the U.S., 2000-2017

Sources: TIA, OIDA, OIDA members

In the transport services market, wireless continues to grow over landline, a trend which is expected to continue. Figure 4 shows that landline subscribers declined 2.9% in 2006 over 2005 and it is believed this trend will continue.

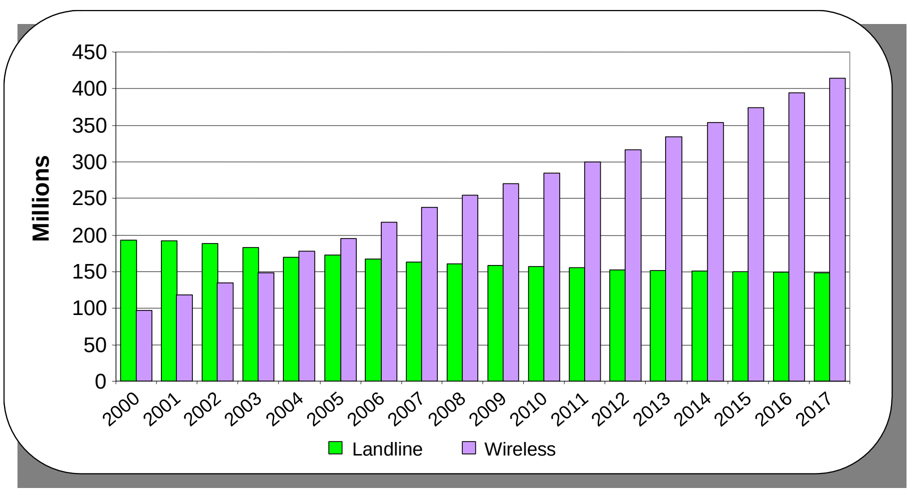


Figure 4: Telephone Subscribers in the U.S., 2000-2017

Sources: TIA, FCC, CTIA, OIDA, OIDA members

In the U.S., the number of wireless telephone subscribers exceeded landline subscribers for the first time in 2004. Wireless subscribers achieved a growth of 11.8% in 2006, up from 2005. Wireless is forecast to grow quickly over the next decade and is expected to have over 400 million subscribers by 2017. Two alleviating factors for the landline subscribers are voice over Internet protocol (VoIP) and Internet TV (IPTV). Both VoIP and video broadband will help maintain a core level of landline subscribers because of low cost phone calls and video services.

Within the landline subscriber arena, there has been a change in the type of internet access connection for the consumer over the last five years. In 2000, the dominant internet access medium was dial-up. Broadband at that time was beginning to show promise, but had only a tenth of the dial-up subscribers, as shown in Figure 5.

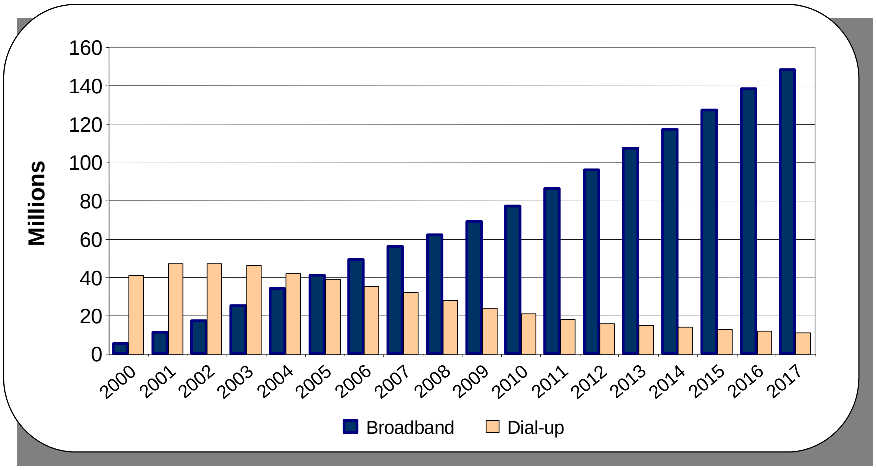


Figure 5: Internet Subscribers in the U.S., 2000-2017

Sources: TIA, FCC, OIDA, OIDA members

The growth of dial-up peaked in 2002 and declined over the last four years with the lower cost of broadband (DSL and cable). The number of dial-up subscribers declined 10.3% in 2006 over 2005, and is expected to continue to decline over the next decade. The declining 2007-2017 CAGR for dial-up is -9.9%. Broadband has grown quickly since 2000 and achieved a growth of 10.6% in 2006 over 2005. It is expected to grow consistently over the next 10 years to nearly 150 million subscribers by 2017.

In the United States, the price of internet access has been dropping significantly. Figure 6 shows the average monthly prices for the U.S. market for both DSL and cable modems.

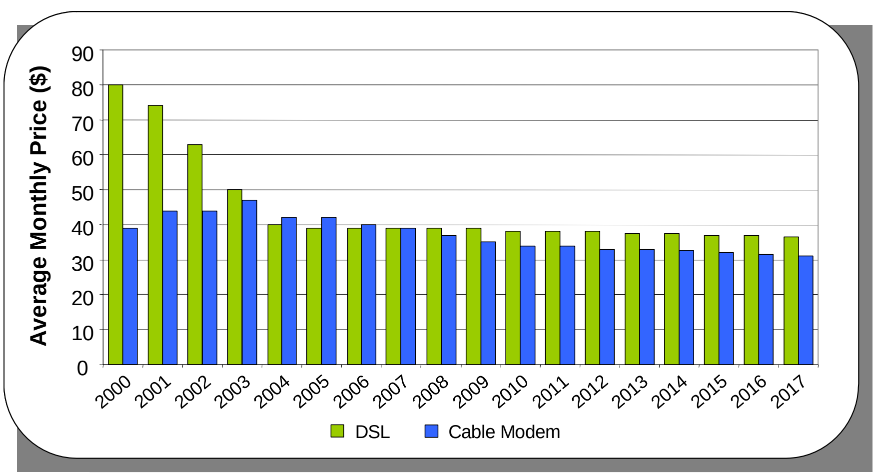


Figure 6: Average Monthly Prices for DSL and Cable Modem, 2000-2017

Sources: TIA, In-Stat, OIDA, OIDA members

2.2 Equipment Market Growth

2.2.1 Demand

Figure 7 shows the growth in traffic on optical networks from 1998 through 2008. The drivers include the growth in broadband subscriptions for telecom and cable companies, the rich media content, and the push for video services by the telecom companies. Goldman Sachs believes we are still in the beginning phases of a significant burst in bandwidth on optical networks.

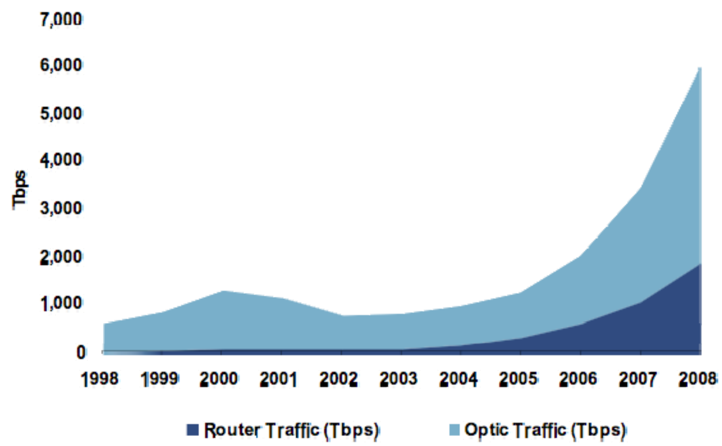


Figure 7: Traffic on Optical Networks (Tbps), 1998-2008

Sources: Goldman Sachs Research, Dell'Oro Research, Infonetics Research

Figure 8 illustrates the fact that growing demand for bandwidth consumed the excess long-haul capacity in the U.S. during 2006.

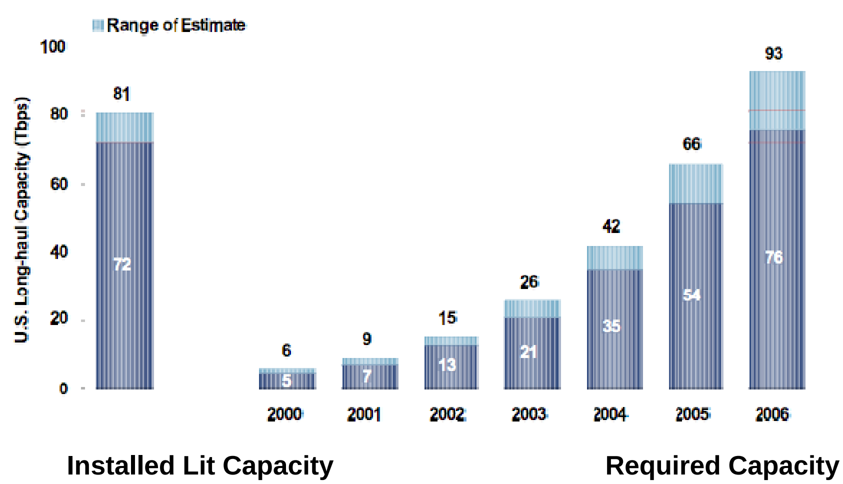


Figure 8: U.S. Long Haul Capacity (Tbps); Demand Has Consumed Excess Capacity

Source: "U.S. Communications Infrastructure: Beyond the Crossroads," an industry study by Goldman, Sachs, and Co. and McKinsey & Co.

2.2.2 Optical Networking Equipment

The global optical networking equipment revenue forecast is shown in Figure 9. In 2006, the optical networking equipment market generated revenue of $12.2 billion, a 15.1% increase over 2005. This followed 17.8% growth in 2005 over 2004. The outlook for the market is strong, with growth expected to top $24 billion by 2017 with a slowing 2007-2017 CAGR of 6.5%.

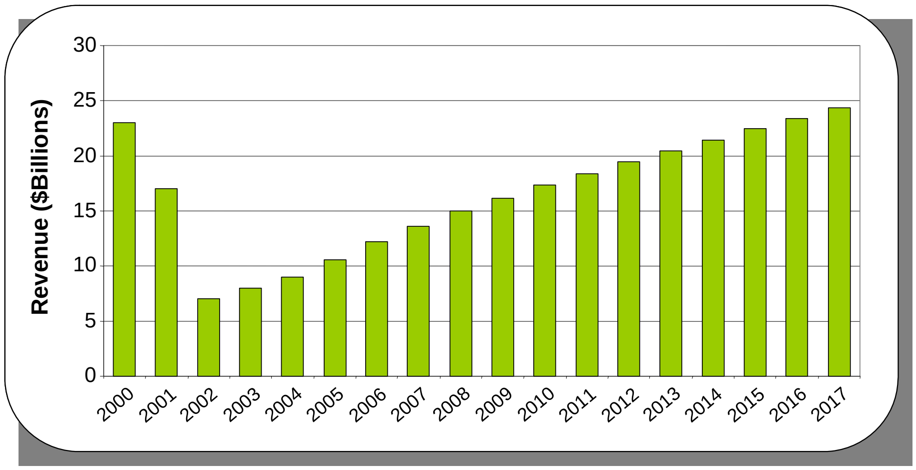


Figure 9: Global Optical Networking Equipment Revenue and Forecast, 2000-2017

Sources: KMI, Infonetics, Ovum-RHK, OIDA member companies, TIA, IDC, CIR, Gartner, Dell'Oro, Aventis, Prudential Equity, OIDA estimates

Figure 10 shows the quarterly optical transport equipment in millions of dollars from the first quarter of 2002 through the second quarter of 2007, based on reported vendor revenues for add/drop multiplexers (ADM), optical core switches (OCS), optical edge devices (OED), and wavelength division multiplexing (WDM) equipment. Since 2003, the market has grown at rates of 10% to 15% per year. The fourth-quarter seasonality marks a return to normal, established business patterns.

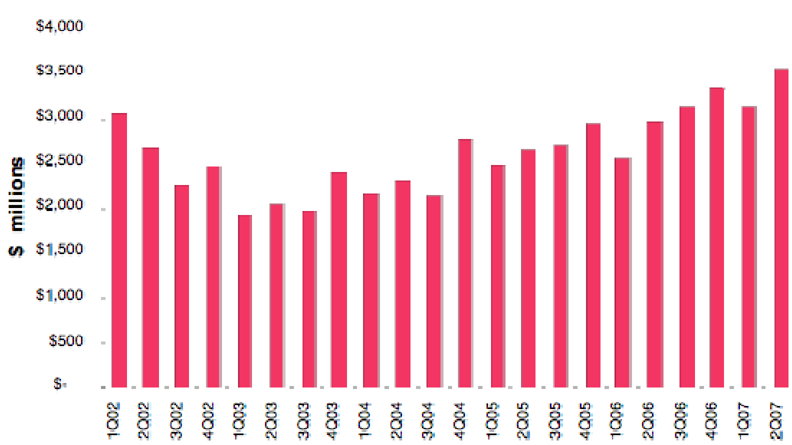


Figure 10: Optical Transport Equipment Market ($M)

Source: Ovum

The communication equipment industry has survived the bubble and returned to health. Figure 11 shows the combined revenue and combined market capitalization in billions of dollars for a representative composite of the communication equipment market, including Ericsson, Motorola, Alcatel-Lucent, Nortel, Cisco, Qualcomm, Ciena, F5, ECI Telecom, Sonus Networks, Juniper, Optium, Opnext, and Adva.

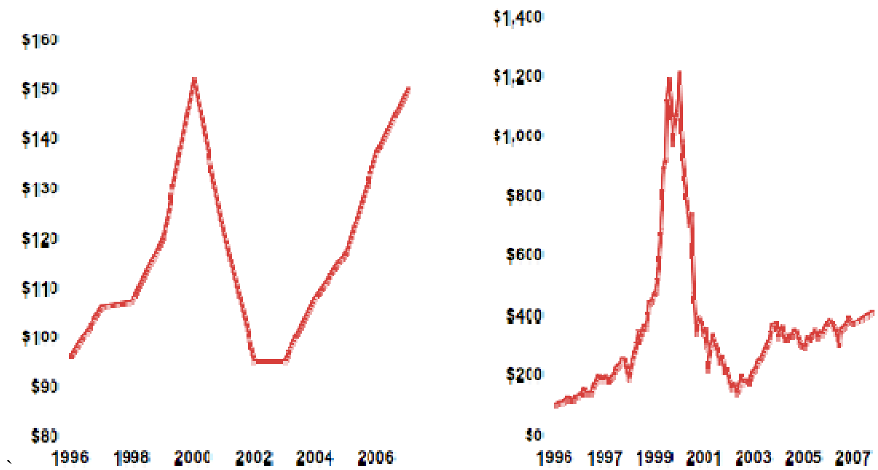


Figure 11: Combined Revenue and Combined Market Capitalization for Communication Equipment Market

Source: Goldman Sachs

Capital expenditures as a percentage of revenue for U.S. wireless and wireline telecom service providers appear in Figure 12.

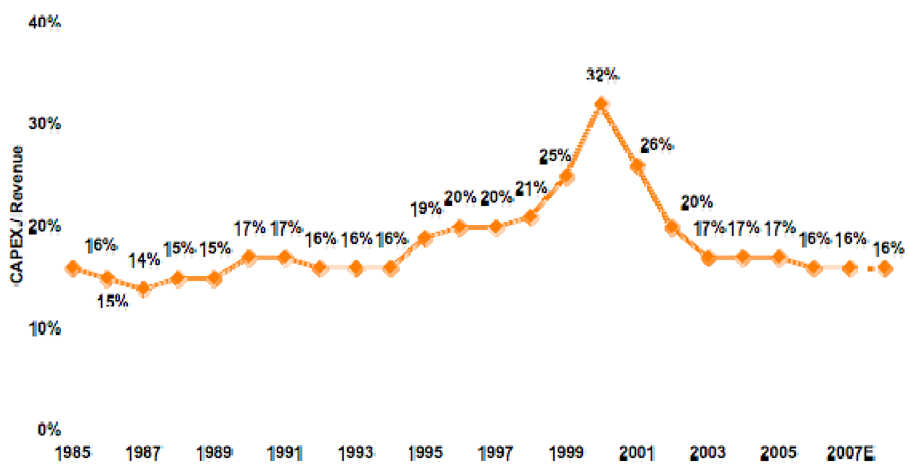


Figure 12: Capital Expenditures as a Percentage of Revenue for U.S. Wireless and Wireline Telecom Service Providers

Sources: Compustat; Wall Street Research Estimates

Figure 13 illustrates the optical recovery; it shows the quarterly revenue ($M) for Ciena and JDSU for the period 1995 through 2007. Ciena revenue showed year-on-year growth of 43% from 2004 to 2005 and 32% from 2005 to 2006. JDSU revenue grew 28% from 2004 to 2005 and 45% from 2005 to 2006.

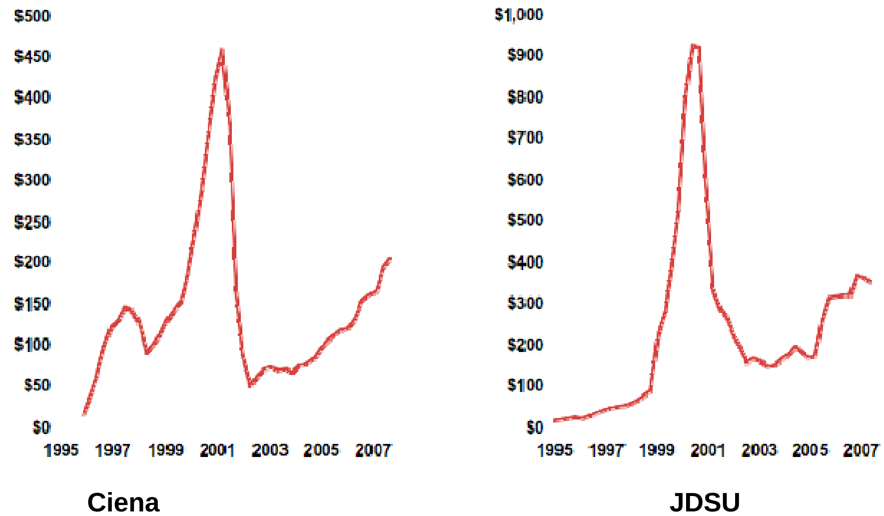
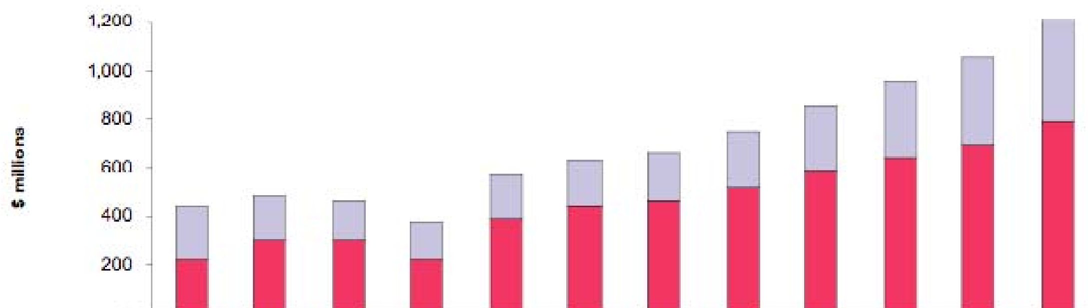


Figure 13: Ciena and JDSU Quarterly Revenue ($M), 1995-2007 (Note Different Y-axis Values)

Source: Goldman Sachs

Optical Transceivers

Figure 14 shows the optical transceiver market and forecast from 2000 to 2011. Ovum forecasts that Ethernet transceivers will grow at a compound annual rate of 10% over the period from 2005 through 2011. Fibre Channel transceivers will grow at a compound annual rate of 14% over the same time period.



	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
Total	$601	$661	$622	$516	$721	$793	$823	$905	$1,026	$1,144	$1,265	$1,462
Fibre Channel	$217	$181	$152	$156	$170	$187	$201	$228	$268	$313	$350	$418
Ethernet	$223	$305	$309	$228	$397	$449	$466	$521	$589	$643	$702	$796

Figure 14: Optical Transceiver Market and Forecast ($M)

Source: Ovum

Shifts in the Equipment Market

The definition of “optical transport” equipment changed significantly between 2005 and 2007 (see Figure 15). Some technologies gained significantly, such as multi-reach DWDM, Metro WDM, OCS (optical switch), and submarine line terminal. Other technologies declined: ADM (SONET add/drop mux), OED (optical edge device or multi-service add/drop mux), DCS (digital cross connect), LH (legacy longhaul), and DWDM.

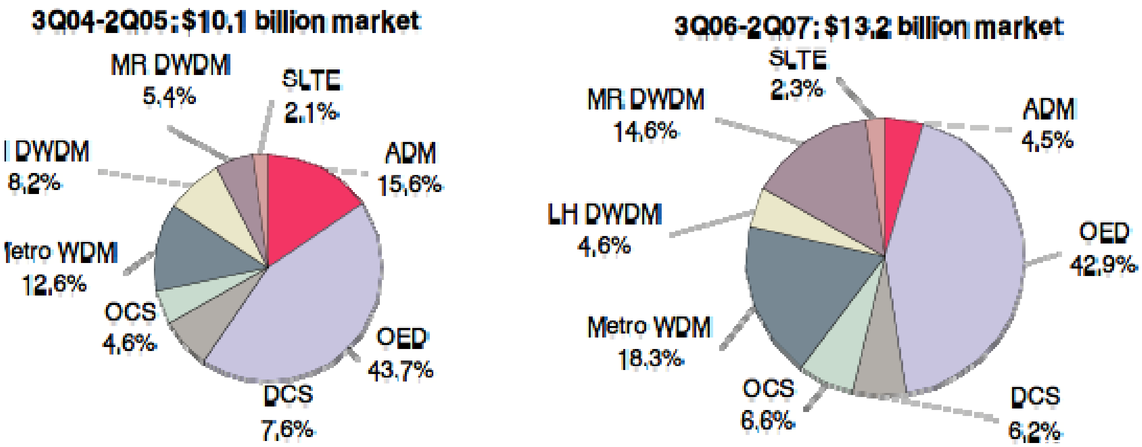


Figure 15: Shifts in Optical Networking

Source: Ovum

The shift from 2.5 G to 10 G network equipment occurred in 2004. Based on 7-year generations, we should expect a transition to 40 G equipment in 2011. However, new low-cost 10 G options may delay the transition. Some equipment providers are saying, “40 G is so hard, we might as well wait for 100 G.” Ovum believes equipment companies will develop 40 G technologies that are compatible with 100 G technologies.

2.2.3 FTTx

Figure 16 shows the growth in North American FTTx connections. FTTx reduces costs by 40% to 60% and also delivers revenue-generating services. AT&T is investing $4.6 billion to roll out FTTx services to 19 million U.S. homes by 2008. Verizon is spending $18 billion to reach 18 million homes by 2010.

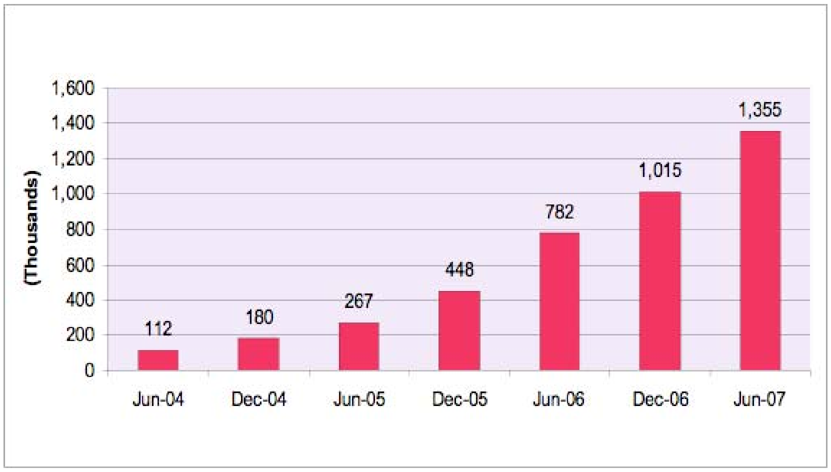


Figure 16: Number of North American FTTx Connections (Thousands)

Source: Ovum

3 Core, Metro, and Access Technology

Demand for bandwidth by consumers and business is continuously increasing. Telecom network carriers are deploying new services and moving into the entertainment and media delivery space. Connectivity, mobility, video, file sharing, peer-to-peer applications, online gaming, security, and networked data backup are pushing new requirements into the telecom operator environment. The amount of data traversing networks is currently growing around 75% year-on-year.

Figure 17 breaks down the traffic across the current AT&T IP network by data type. This growth in traffic includes network from the merger with SBC communications. Peer-to-peer and Web-based applications have been growing significantly. Network traffic grew by a factor of five over five years.

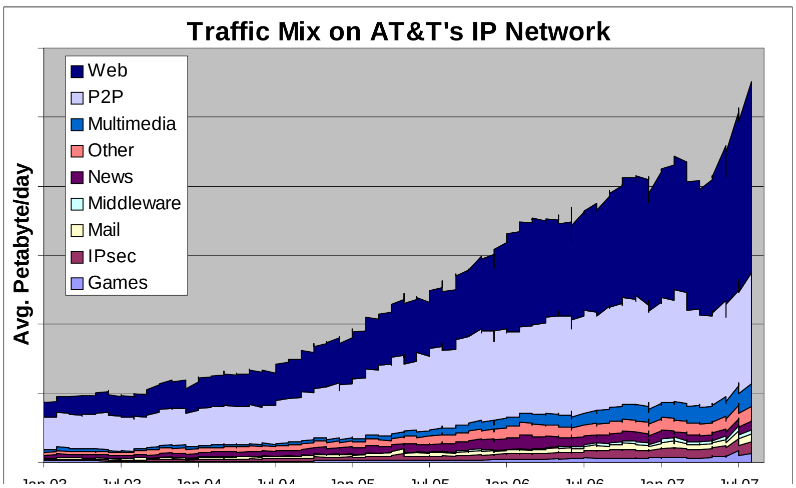


Figure 17: Growth in IP Traffic across the AT&T Network

Source: AT&T

The networks of carriers, municipalities, and cable companies are changing and expanding. Wireless carriers are backhauling their traffic across the fiber based network. The next sections highlight some of the aspects of the network today.

3.1 Network Overview

The network has three key segments: the core, the metro, and access. We can also segment the network infrastructure by distance, application, and protocol.

The transport of information over the network is standardized. Several standards bodies define the technology implementations and specifications for the network structure, including the Optical Internetworking Forum (OIF), Institute of Electrical and Electronic Engineers (IEEE), Internet Engineering Task Force (IETF), International Telecommunications Union (ITU), and the Telecom Industry Association (TIA).

Several protocols co-exist at various points in the network. In the transport environment, the principal protocol is OTN, which is effectively a digital wrapper. It receives a payload of information handed off at a service point and wraps it in order to transport it over a carrier's network. As the carriers must all interoperate, the OTN transport must be seamless as the data traverses multiple operators' switches. Network management and control plane software are key elements of today's networks. Fast restoration and re-route are important parts of the network.

Outside the carrier networks, the enterprise and data centers operate with different protocols and management. In today's data centers, multiple competing protocols manage the flow of data between servers. Table 1 highlights the different protocols within the data center environment:

	Server to Server		Card to Card	Intra-Card
Length	10 - 300m	1-10m	0.3 - 1m	0.1 - 0.3m
No. of lines per link	1	1-10	1-10	1-100's
No. lines per system	10's	10-1000's	10-1000's	10-1000's
Standards	LAN/SAN Ethernet Fiber Channel Infiniband	Design Specific LAN/SAN Ethernet Fiber Channel Infiniband	Design Specific Ethernet - Infiniband PCI	Design Specific
Fiber Optic Transmission	Yes	Yes	?	?

Table 1: Different Protocols Utilized in Today's Data Center Environment

Source: 100 Gbit Interconnects and Above OIDA Forum Report

The data center protocols are handed off to the transport network and must be managed when connected to the wide area network (WAN). Typically, the OTN transport box must know whether an Ethernet connection or another protocol is being handed off.

In today's information society, multiple networks interoperate, including private line, leased line, and Enterprise and Web server connections. The amalgam of different private and leased line networks depends on the companies involved. Several institutions and companies run their own private enterprise networks over leased lines. Financial institutions maintain their own private networks for security. Both cable and telecom operators sell bandwidth and private lines, in addition to supporting the public network.

Each segment of the network levels relies on the key technologies of optical, electrical or RF signaling, transport, and connection. Figure 18 provides a simple view of the communications network structure.

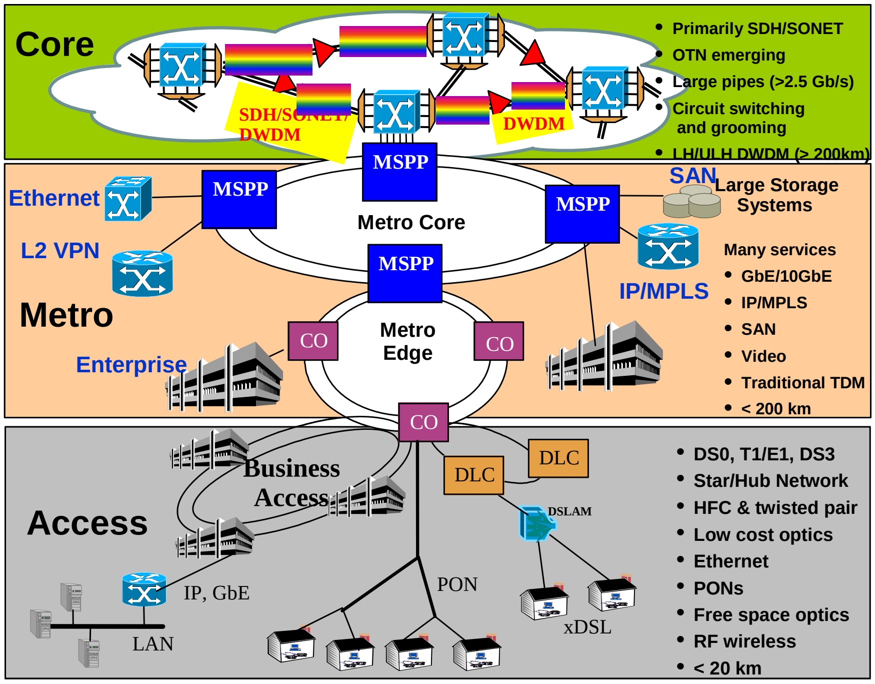


Figure 18: Network Overview from 2005

Courtesy of Ann Von Leman: OIDA Optical Networking and Broadband Report 2005

The network structure in each segment originates from the Open Systems Interconnection (OSI) Model, defined by the International Standards Organization (ISO) and illustrated below:

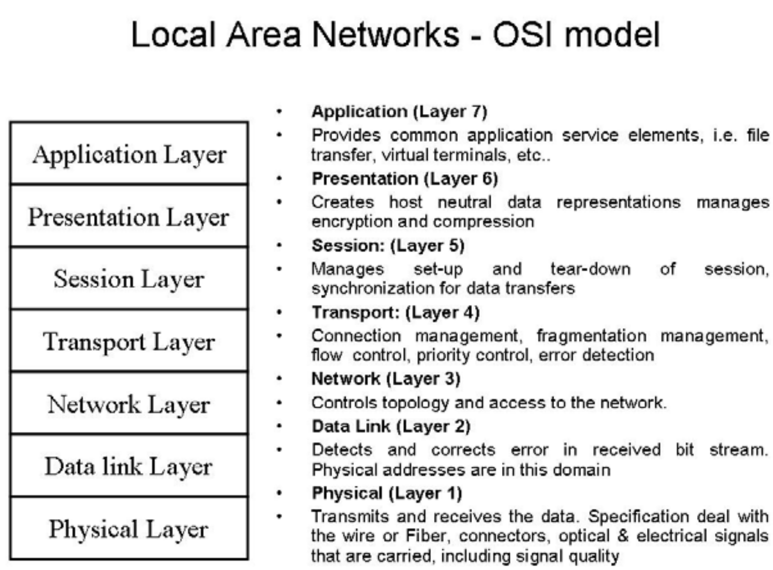


Figure 19: Overview of the OSI Reference Model for Communications

Source: Private Communication - Bill Ring

The primary protocol of choice for current networks is the Internet protocol, which sits at Layer 3 in the OSI reference model. The core of the network resides at the highest level where the aggregation from the metro and access points meet for transport.

The way in which the packets travel across the network depends on the traffic management and network architecture employed. Today, most telecom carriers manage the IP traffic via multi-protocol label switching or M-PLS (e.g., AT&T) and OTN/SONET. The carriers rely on DWDM for point-to-point transmission. Today for transport networks, Ethernet traffic is encapsulated in the optical transport network with a wrapper such as virtual concatenation (VCAT) or globally pseudochronous locally synchronous (GPLS).

With the current growth in demand for Ethernet access to the OTN, carriers are investing in carrier-class Ethernet. OEMs are developing new protocols such as provider backbone transport (PBT), provider backbone bridging transport (PBBT) and transport multiple protocol label switching (T-MPLS).

3.2 Core Network

The core network is the top level in the aggregation tree. In the core of the network, DWDM and OTN account for most of the transport. Figure 20 shows the long-haul network of AT&T.

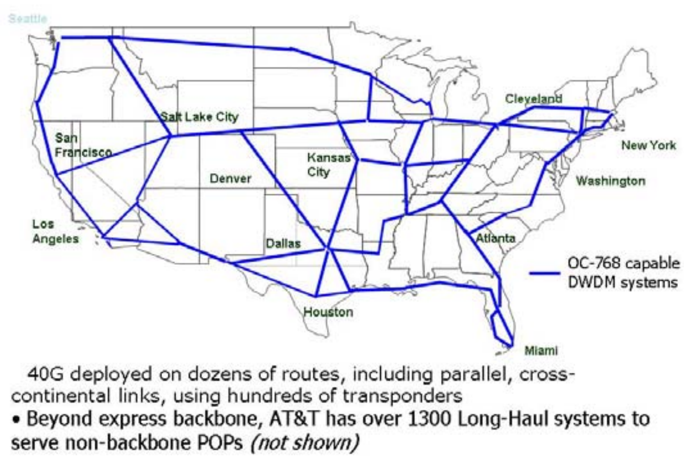


Figure 20: Example of the AT&T Long Haul Network Infrastructure

Source: AT&T

These long distance routes require high bandwidth capacity as the access points load the network with more transport information. Interoperability and hand-off are important features for telecom networks. Carriers work under service level agreements (SLA) to ensure service quality and up-time to customers. They provision the network with an intelligent control plane structure. Figure 21 shows an example of the control plane.

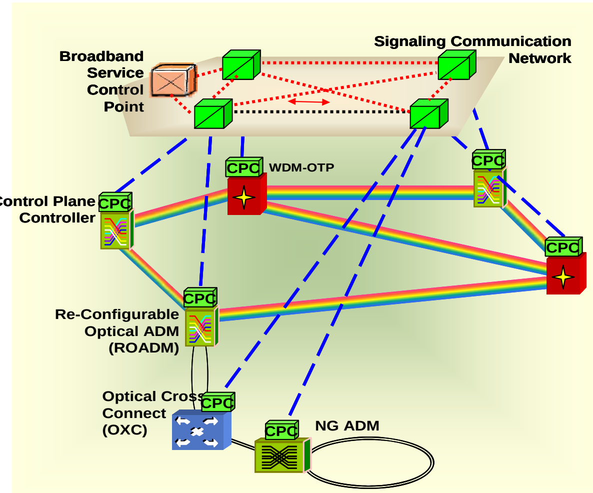


Figure 21: Intelligent Control Plane Based on Reconfigurable Network

Sources: Stuart Elby, Verizon; Private Communication

3.2.1 Optical Transport Network

Transport over the network typically occurs via the optical transport network (OTN, or G709). The OTN is a wrapper technology. Figure 22 shows the layers for transport in the carrier environment:

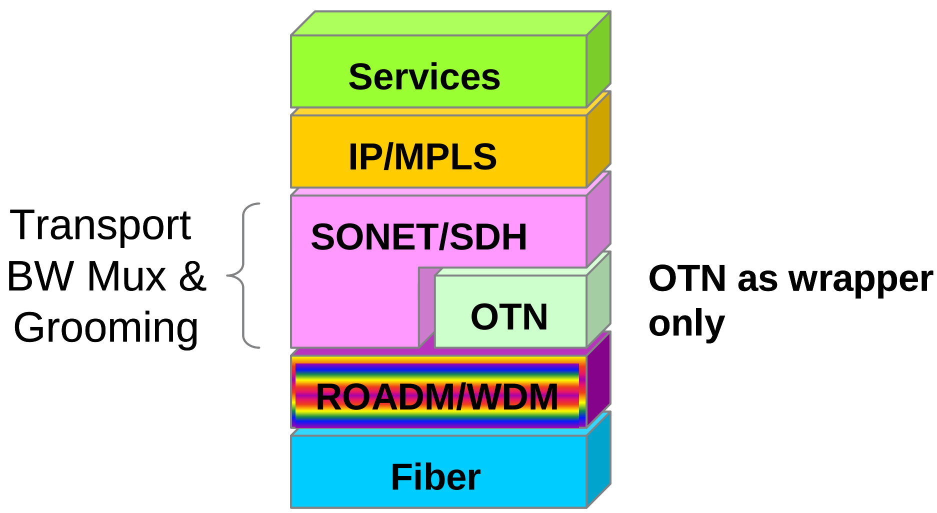


Figure 22: Layer Structure for Transport Today

Sources: Stuart Elby, Verizon; Private Communication

3.2.2 SONET / SDH

A large amount of SONET/SDH legacy equipment remains in operation. The SONET/SDH system has been the workhorse of the telecom carrier for more than 20 years. The system originally developed around voice telephony and circuit switching. The ITU has upgraded SONET specifications to allow higher data rates and to map other protocols in-

to a SONET frame for more efficient transport around the carrier network. SONET/ SDH systems offer high reliability, and they ensure quality of service and interoperability for the carriers.

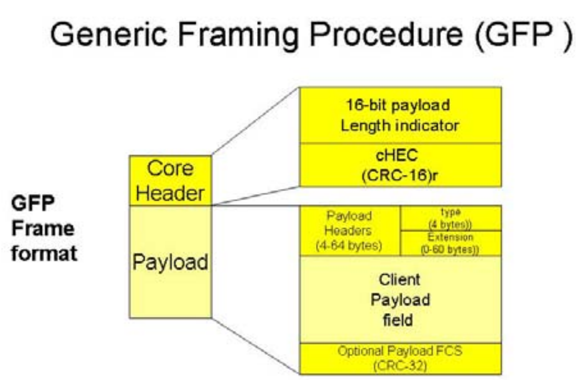
The basic building block of the SONET/SDH system is a minimum packet size or line rate. The primary packet size defines the hierarchy. All the higher levels are multiplexes of the lower level modules. Table 2 shows the standardized line rates.

SDH	***SONET***	***Line Rate***
	OC-1	51.84MBit/s
STM-1	OC-3	155.52MBit/s
STM-4	OC-12	622.08MBit/s
	OC-24	1244.16MBit/s
STM-16	OC-48	2488.32MBit/s
STM-64	OC-192	9953.28MBit/s
STM-256	OC-768	398813.12MBit/s

Table 2: Line Rates for SONET/SDH Systems as Defined by the ITU

Source: International Telecommunications Union ITU.G Line Rates

The basic packet used in SONET/SDH has a payload and a header. With the crossover to more data traffic, the ITU introduced the generic framing procedure (GFP) for the SONET/SDH system (Figure 23). The GFP made it possible to encapsulate data onto the SONET backbone more efficiently. The efficiency of data transport increased significantly with the introduction of virtual concatenation.



Client Payload (unecnoded Bandwidth/Line Rate)	SONET/SDH path (Bandwidth)
ESCON (160/200Mbs)	STS-1-4v/VC-3-4v (196Mb/s)
Fiber Channel - FC100 (850/1062.5Mb/s)	STS-3c-6v/VC-4-6v (900Mb/s)
FICON (850/1062.5 Mb/s)	STS-3c-6v/VC-4-6v (900Mb/s)
Gigabit Ethernet (1000/1250 Mb/s)	STS-3c-7v/VC-4-7v (105Mb/s)

Figure 23: Generic Framing Procedure Used in SONET/SDH Networks

Source: International Telecommunications Union

The telephone companies rely on their SONET/SDH and DWDM links for transport. The ITU is developing the next generation network (NGN) and the advances required to facilitate new services. One of these advances is the IP multimedia subsystems (IMS). The goals of IMS are to enable seamless connectivity between mobile and fixed networks and to upgrade the current network infrastructure.

The network must transport and integrate several different types of protocol stacks, as shown below.

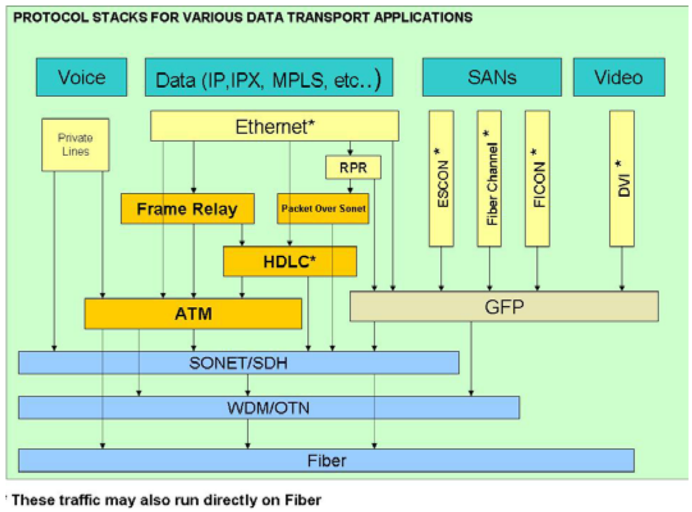


Figure 24: Protocol Stacks for Various Data Transport Applications

Source: 100 Gbit Interconnects and Above OIDA Forum Report

3.2.3 Ethernet

The Ethernet network resides in Layer 2 of the OSI model. Its functions are defined by standards developed through the IEEE. The original Ethernet local area network (LAN) architecture has evolved since its inception in 1973. The original Ethernet network used a half-duplex technology with carrier sensed multiple access/collision detection (CSMA/CD). As it developed, it moved to duplex operation, enabling the removal of collision detection, which can cause network slowdown. During the 1990s, the move to a switched-based architecture expanded the availability of Ethernet.

Level 2 of the OSI model expands within Ethernet at the data link and physical layers. The architecture in the data link layer at Level 2 is subdivided in the logic link control (LLC) and the media access control (MAC), as shown in Figure 25.

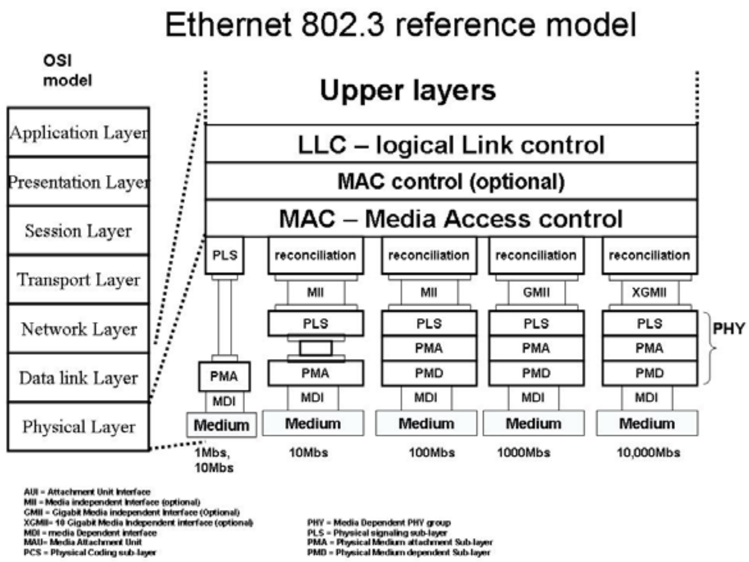


Figure 25: IEEE 802.3 Reference Model Up to 10 Gbit/s Data Rates per the IEEE Documents

Source: 100 Gbit Interconnects and Above OIDA Forum Report

The LLC defines the common interface to the network layer. It provides interface points called service access points (SAP). The MAC layer and the physical layer implement media-specific functions. For example, the MAC communicates directly with a computer network interface card.

3.3 Metro Network

Today, "carrier-grade" Ethernet is expanding into the service provider backbone. The Metro Ethernet Forum (MEF), initiated in June 2001, has worked on scalability and other issues to enable Ethernet to move into the provider network. These changes were required as the carriers prefer determinism, while the enterprise customer prefer plug and play. A carrier operator is typically looking for these characteristics:

- Open and standard interface
- Simplified network architecture
- Scalability
- Reliability
- Enhanced charging functions
- Enhanced security
- Quality of service

The early Ethernet network was a best-effort delivery system. The evolution of Ethernet now provides ways to manage information differently for different user classes. The MEF has defined specifications which allow Ethernet to act like a service. As a result, Ethernet equipment can now achieve the carriers' key requirements. The MEF certifies the equipment produced by its partners and members to enable deployment against a common

standard. The next-generation Ethernet network requires a provider backbone bridge, as defined by 802.1ah. In this specification, each 802.1ah level encapsulates frames with a new MAC address and a new service tag. The nesting level summarizes the MAC addresses of the lower level with a backbone MAC address. The end result is that Ethernet deployment in the metro has evolved into a realistic and reliable service solution.

In the U.S., most of the connections are made by copper. Figure 26 highlights the copper connections to the metro rings.

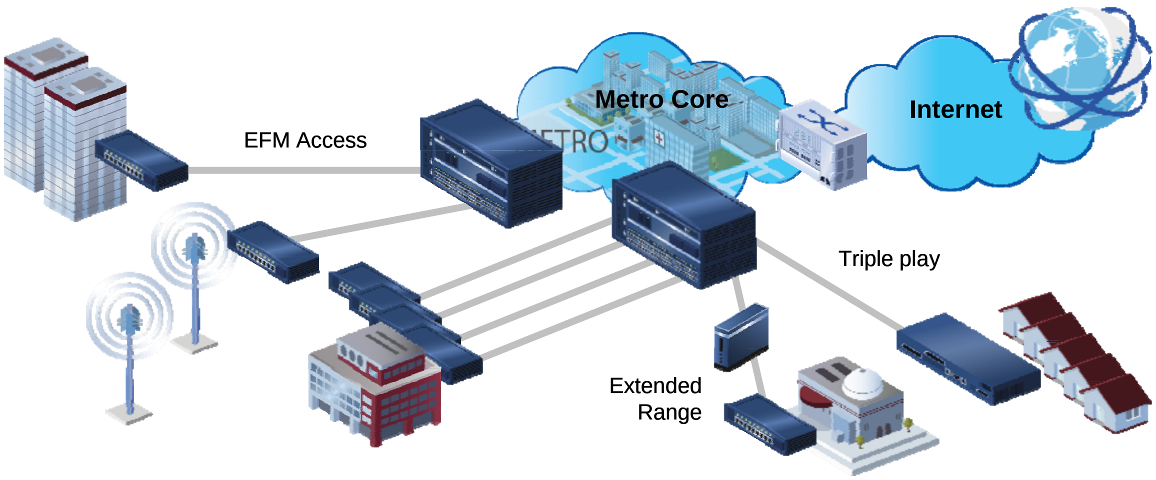


Figure 26: Carrier Ethernet Copper Plant in the Metro Network

Source: Anda Networks

Carrier Ethernet is growing in deployment within the North American market. Figure 27 shows an example of the fiber connections to the metro rings.

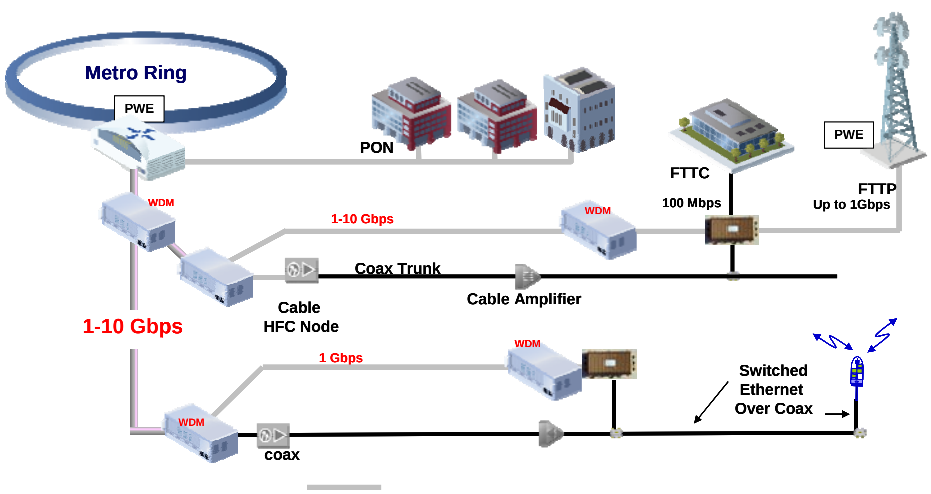


Figure 27: Fiber Plant for the Carrier Ethernet Market

Source: Anda Networks

Carrier Ethernet can provide global connectivity between provisioned sets of network interfaces. Effectively, carrier Ethernet is a global virtual private network multiplexing technology.

It is unclear whether Ethernet can become the protocol and delivery system. There are still many industry obstacles to overcome before it could be the protocol of choice. The issue today is that if we look at the actual amount of transport of Ethernet data in the global network, 50% of it is still transported over a SONET/SDH link.

4 Access Networks

Various technologies compete at the edge of the network. Consumers and enterprise users rely on one of these technologies for access:

- DSL modem (twisted pair)
- Cable modem (Coax)
- Fiber optic cable (SMF)
- Satellite (RF)
- WiMAX (RF)

The access point is the "ramp" for information, i.e., data, voice or video. The different access nodes can be either passive or active, depending on the connection type employed by the subscriber. Current "on-ramps," or connections to the Internet, are mainly DSL, cable modem, or ISDN (T1 or E1) lines. In other words, most connections are copper based and therefore limited in speed and distance (i.e., distance x speed is fixed). The question is whether cable companies or telephone operators will install fiber for high-speed access. Their decision depends on both legislation and demand. Table 3 compares the access technologies.

	Copper DSL Bonding	PDH Circuit Bonding	Dark Fiber	Wireless
Availability/ Reach	**Medium**-good for CSA Iintralata distances over	**High**-T1/E1 can be used IntraLATA, Inter- LATA and	**Low**-Only 11% fiber connected businesses in	**High**-Can be deployed anywhere unlicensed;
Transport Cost	**Low**-can use binder group pairs/unbundled loops if available	**Medium**-T1/E1 wholesale services now a commodity	**High** – cost/time to deploy fiber is lengthy and can incur NRE	**Low**-Cost of Base stations and licenses
Reliability	**Medium**-Must compensate for varying copper loop quality	**High**-same as existing T1/E1 and SONET/SDH	**High**-highest nines once deployed	**Lowest**– tuning and licensed spectrum required
Security	**Medium**-Same as local loops in binders	**Medium**-Same as T1/E1 and SONET/SDH	**HIGH**-most secure	**Lowest**-Requires sec. encryption
Regulatory	Good for incumbent carriers with access to local binder facilities; tough out of region	Global carriers, IXC's and CLECS using Type 2 networks today	All carriers but must offer retail and whole- sale unbundled service elements	Requires Licensed spectrum ideally;good for rural and DSL/cable fill in with no copper
Port Density	**Low**- Up to 40 pairs per box max. 40 subs	**High**-1000's of subs.	**High**-1000's of subs.	**Medium**-100's of subs per base-station
OPEX	**Medium**-requires book ending-repeaters for addl. distance	**Low**-can bookend, aggregate or terminate on 3rd parties	**Low**-can bookend or terminate on 3rd parties	**Medium**-requires calibration and effective spectrum planning
Speed	**Low**: ~ 1-45Mbps	**Medium**: ~1Mbps-1 G	**High**: 1Mbps-10Gig+	**Low**: ~ 1-20Mbps
Access Box	~$1000-$3000 USD	~$1000-$2000 USD	~$500-$2000 USD	~$1500-$3000 USD

Table 3: Comparison of Access Technologies

Source: Anda Networks

The access network is a bottleneck. The amount of fiber deployed in the U.S. has increased significantly in the last two years, but the U.S. still lags other countries in deployment. The annual installation of fiber miles peaked in 2000 at 19.6 million miles, crashed dramatically to only 4.8 million miles in 2004, and grew steadily to about 10.9

million miles in 2007 (see Figure 28). Currently only about 2% of U.S. subscribers and 13.4% of enterprise customer buildings in the United States connect with fiber.

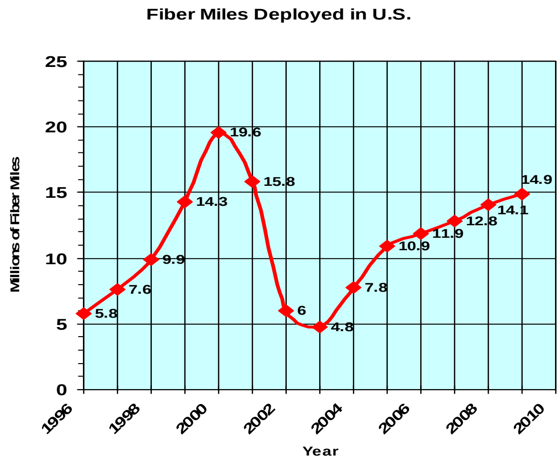


Figure 28: Fiber Miles Deployed in the U.S., 1996-2010

Source: Anda Networks

Ethernet access deployment is increasing in the business environment. New services such as E-line and E-LAN are gaining acceptance among business customers. Ethernet service at the wireless access points is also growing in popularity.

4.1 FTTX – Residential Broadband

The consumer connection is the current high-growth area for access nodes. Students, adults, and small business owners are connecting to the Internet at high download and upload speeds. E-commerce and electronic transactions are becoming more common within consumer networks. Many consumers connect to the network by copper access points, either DSL or coax cable modems. Figure 29 provides an overview of the current access infrastructure.

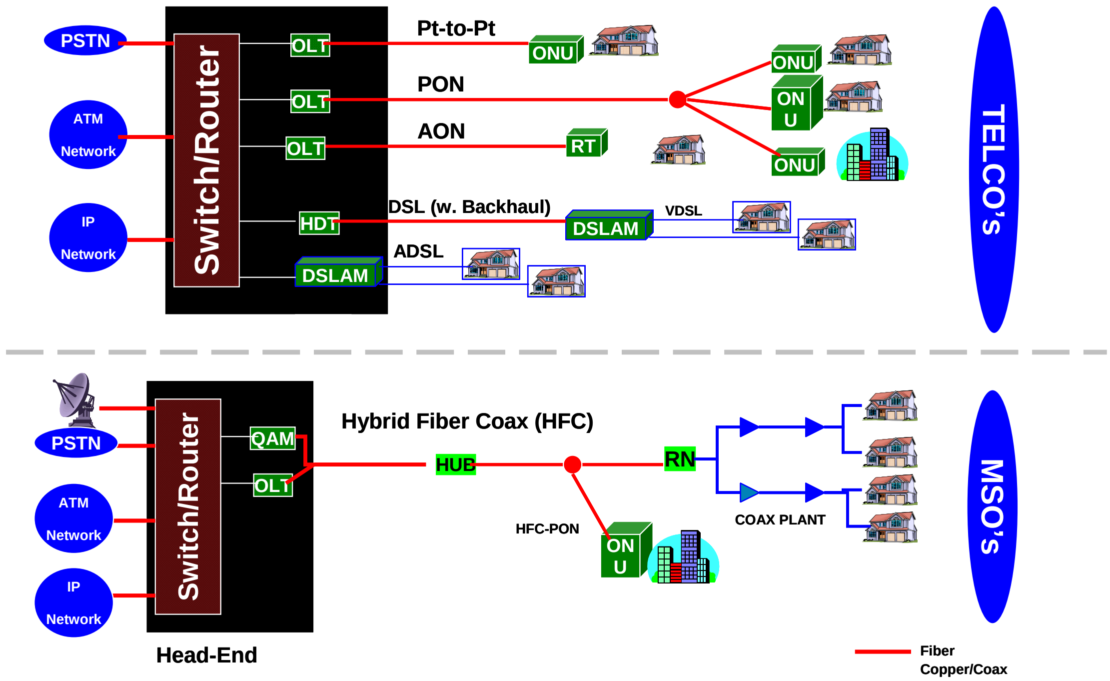


Figure 29: Access Architectures Deployed in Networks Today

Source: Cisco Systems

The majority of households connect by wire line (cable or DSL). Within the U.S., the cable modem is the most common connection.

Alternatives to the wire line connection include Wi-Fi and WiMAX. The broadband WiMAX service targets the mobile worker. The current use of WiMAX offers the capability to roam yet remain connected to your IP network. The T-Mobile 'home' hotspot allows cellular customers to use Wi-Fi access for VoIP calls while roaming inside their residence or at hotspots outside, e.g., Borders, Starbucks, and airport lounges. Several new dual-mode phones with Wi-Fi/global system for mobile communication (GSM) capabilities have entered the market to provide this service. The impact of this service on the home networking and voice market is unclear at the moment.

Within the home environment, several new technology approaches have entered the market to address home networking. One alternative 'wired' network infrastructure connects all the networked appliances with low-cost plastic optical fiber. Low cost 650 nm sources and receivers, based on the media oriented systems transport (MOST) transceiver technology found in automobiles, are available. Home networking is a key area for the access market as it drives bandwidth demand at the edge of the network.

Several telecom carriers have programs backed by government (Japan/Korea) or by regulation (Verizon) to connect the consumer to the fiber optic network. Fiber offers several advantages over copper connections:

- Virtually unlimited bandwidth
- No crosstalk
- No EMC issues (neither passive nor active)

Fiber offers other distinct advantages in new deployments:

- Fiber is cheaper than copper wire.
- Fiber cables are smaller than copper cable.
- Fiber cable has no value on the scrap market.

We expect that consumer bandwidth requirements will continue to increase at a minimum rate of 30% per year, as shown in Figure 30.

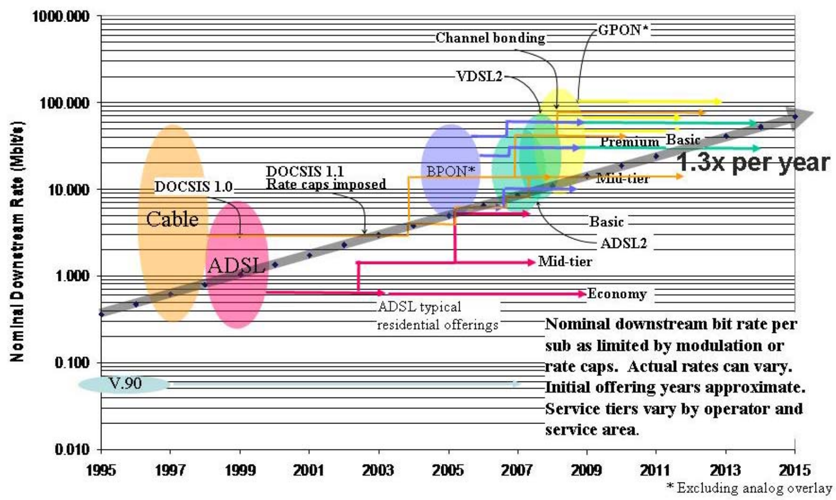


Figure 30: Trend in Downstream Service Rates

Source: Motorola

By 2012, the access rate will exceed the capability of copper solutions and will require fiber deployment. In response, the core and metro networks will need to provide high-bandwidth capacity due to the increase in access ramps to the network.

FTTx networks are based on different access structures:

- Tree architectures: Passive optical network technology
- Star architectures: Point-to-point connection of customers to switches in a star topology
- Ring architectures of Ethernet switches: Interconnection of switches by gigabit Ethernet in a ring topology

The exact topologies can be mixed and matched in a single network. Figure 31 shows the network architecture for both EP2P and PON.

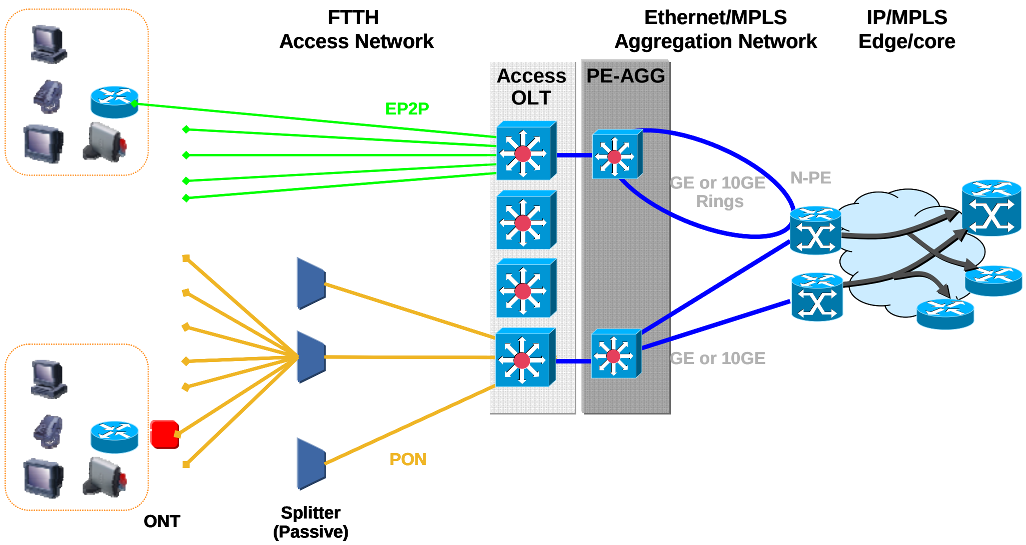


Figure 31: Comparison of the Fiber Access Infrastructure Connections for FTTx

Source: Cisco Systems

The number of FTTH subscribers worldwide exceeded 10 million in early 2006. Figure 32 projects worldwide subscriber growth in FTTH. In 2009, PON will have 28.9 million subscribers and EP2P will have 2.3 million. The number of FTTH subscribers in North America as of October 2007, over 2 million, is also identified in Figure 32.

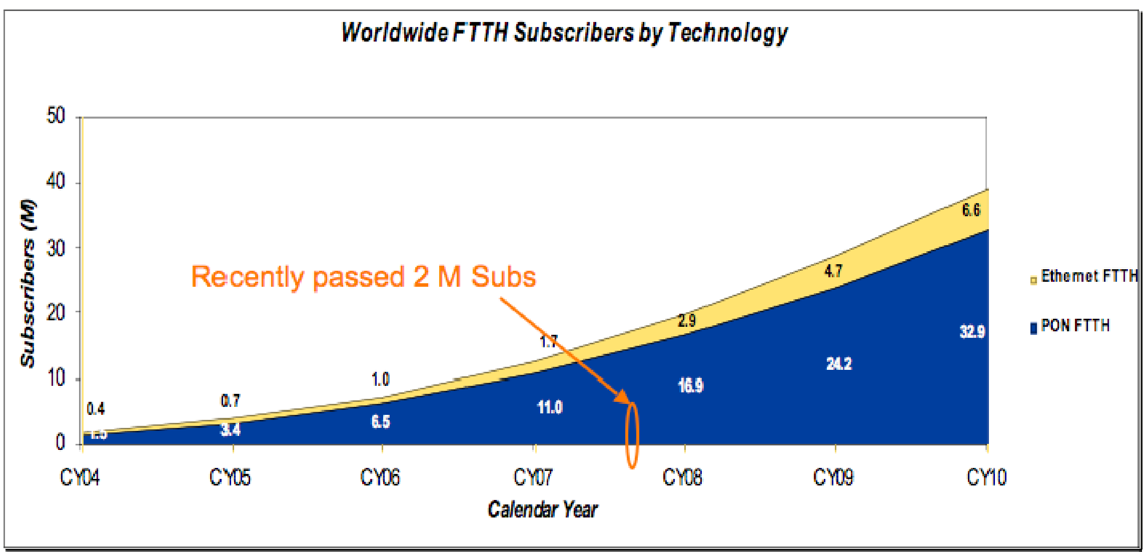


Figure 32: Worldwide Fiber to the Home Subscribers by Fiber Network Type

Source: Motorola

The number of connections is growing fastest in South East Asia. Both South Korea and Japan have aggressive fiber to the home connection projects. Within Korea, the govern-

ment is pushing to connect 100% of households to the network by fiber. Figure 33 shows the expected growth by region.

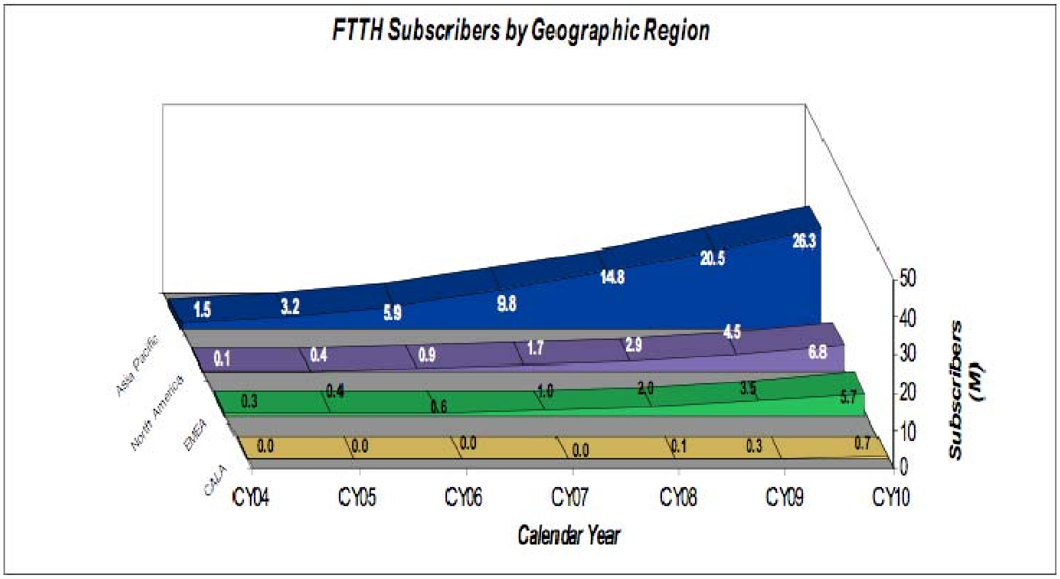


Figure 33: Growth in FTTx Connections by Region

Source: Motorola

There are several points to consider with respect to FTTx systems for the consumer:

- Fiber deployment to residences requires a large investment into the future.
- Every deployment scheme for FTTH networks has its own merits.
- PONs minimize short-term deployment cost, but they build bottlenecks into the physical infrastructure.
- Star architectures can provide virtually unlimited bit rates to subscribers. The carriers can upgrade individual subscribers to more powerful technologies as needed without impacting the service to other subscribers.

Point-to-Point Networks

The current EP2P network architecture is based on a star topology.

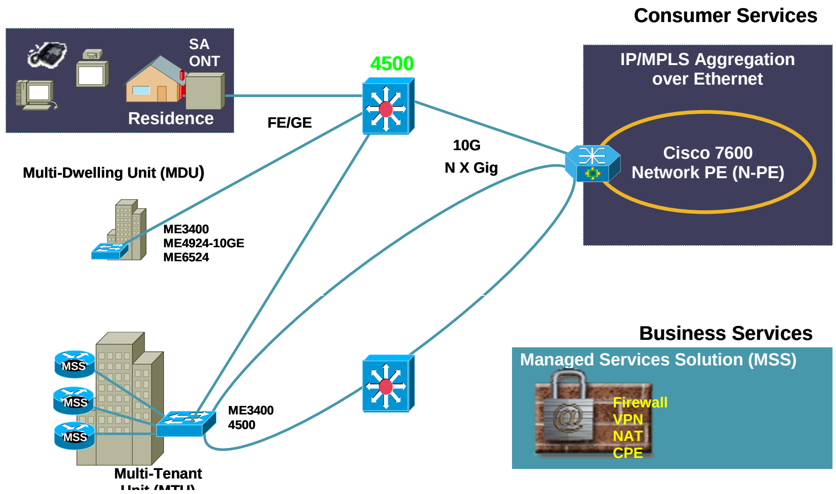


Figure 34: EP2P Network Architecture Using a Star Topology

Source: Cisco Systems

Figure 35 shows the current projection for EP2P subscriber growth.

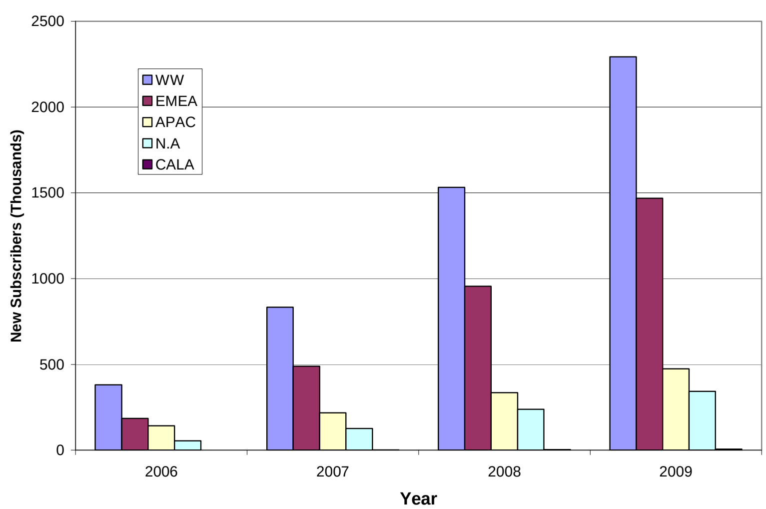
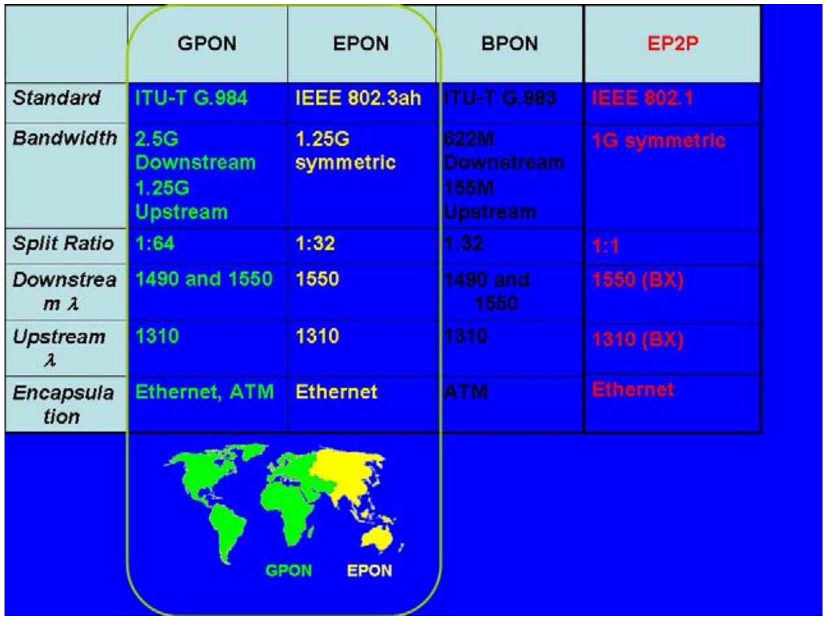


Figure 35: Projection of EP2P Network Deployment and Subscriber Growth

Source: Cisco Systems

Passive Optical Networks

Within the PON access market, different fiber optic protocols are deployed. The connections are standardized under both the ITU and IEEE. Figure 36 lists the key features of these protocols.



	GPON	EPON	BPON	EP2P
Standard	ITU-T G.984	IEEE 802.3ah	ITU-T G.983	IEEE 802.1
Bandwidth	2.5G Downstream 1.25G Upstream	1.25G symmetric	622M Downstream 155M Upstream	1G symmetric
Split Ratio	1:64	1:32	1:32	1:1
Downstream λ	1490 and 1550	1550	1490 and 1550	1550 (BX)
Upstream λ	1310	1310	1310	1310 (BX)
Encapsulation	Ethernet, ATM	Ethernet	ATM	Ethernet

Figure 36: Current Overview of the Outlay in Fiber to the Home Network

Source: Cisco Systems

In Asia, Ethernet passive optical network (EPON) deployment is more popular than GPON. GPON has replaced broadband passive optical network (BPON) as the next step in FTTx rollout. The architecture of the current passive optical network and the requirement to split the light at a node raise several issues:

- All users on the tree share bandwidth.
- Strong encryption is required to prevent eavesdropping.
- Large overhead reduces useable throughput.
- Every endpoint has to operate at the aggregate bit rate (e.g., a GPON optical network terminal delivering 100 Mbit/s to an end customer has to operate at 2.5 Gbit/s).
- Significantly higher optical power is required, e.g., 20.4 dB (power ratio of 110) for a 1:64 split.

Future PON Upgrade Options

There are three main candidates for upgrading next-generation PON deployments to increase the data rate to the user:

- Long-reach PON
- D-WDM PON
- Hybrid TDM/WDM networks

Long-Reach PON

Long-reach PON in the network offers several potential advantages for the carrier. The principal one is the collapse of the metro and access points into one level in the current

architecture. This collapse would decrease the number of central office (CO) locations for the network (i.e., huts) and thereby reduce the operating cost for the network.

Currently, BT is investing $19 billion in its 21C network upgrade, which began in 2003. The access points for this network are Ethernet based. The network changes are aimed at reducing both the CAPEX and OPEX requirements for the network. The long-reach PON option, which could incorporate WDM, is a consideration for the next upgrade cycle after 21C is completed.

D-WDM PON

The second option of D-WDM is to provide a dedicated wavelength to each subscriber at the optical network unit (ONU). In this option, each subscriber receives a dedicated wavelength. The WDM overlay is assumed for both upstream and down stream traffic. Figure 37 illustrates this concept.

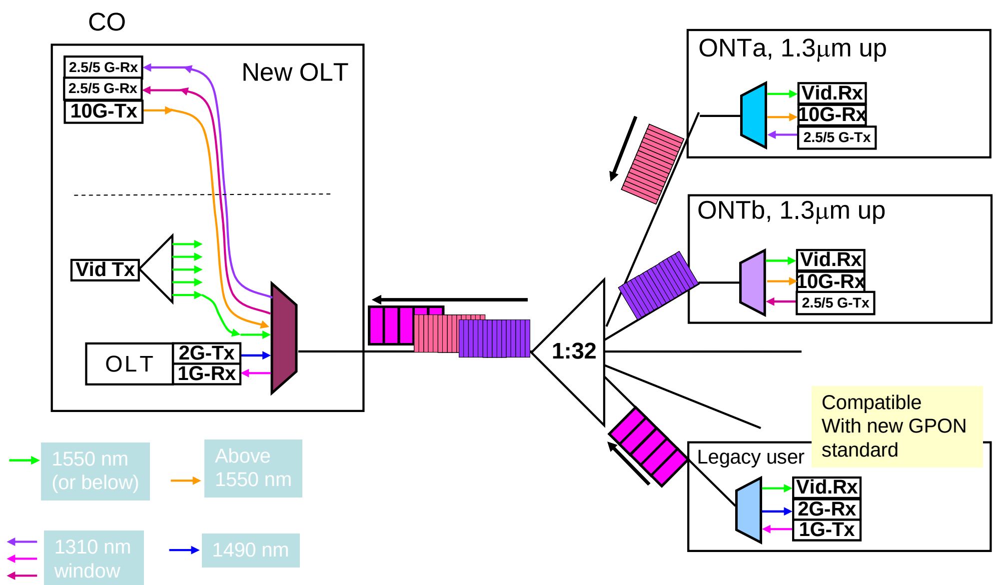


Figure 37: D-WDM PON

Source: Telcordia Technologies

WDM PON offers these advantages:

- Isolation between new WDM overlay and legacy PON
- Both upstream channels clocked/controlled from single downstream
- CWDM should permit uncooled ONT transmitters
- Upstream at 1.3 µm, directly modulated laser due to low dispersion
- Add second upstream when needed
- Achieve 2:1 asymmetry with 2.5 G burst-mode receivers, 1:1 asymmetry with 5 G burst-mode receivers

- Two new upstreams could be at different rates
- Most of C/L-band remains free for later DWDM uses

The principal disadvantages of this approach include:

- Two new DIFFERENT ONT types needed, inventory, etc.
- New burst-mode receivers at 2.5/5 Gb/s
- 3 new wavelengths on PON
- Added WDM losses for existing GPON system

Hybrid TDM/WDM Networks

The alternative approach under consideration to upgrade the PON networks is to use a hybrid TDM/WDM network. In this approach, there is a 10 G downstream overlay at 1.5 µm. The upstream uses a time division multiple access (TDMA) interleaved system with a TDMA upstream signal at 1.3 µm and a multi-rate burst mode receiver. The main features of this approach are the requirements for only one new ONT type and the burst mode receiver at the optical line terminal (OLT).

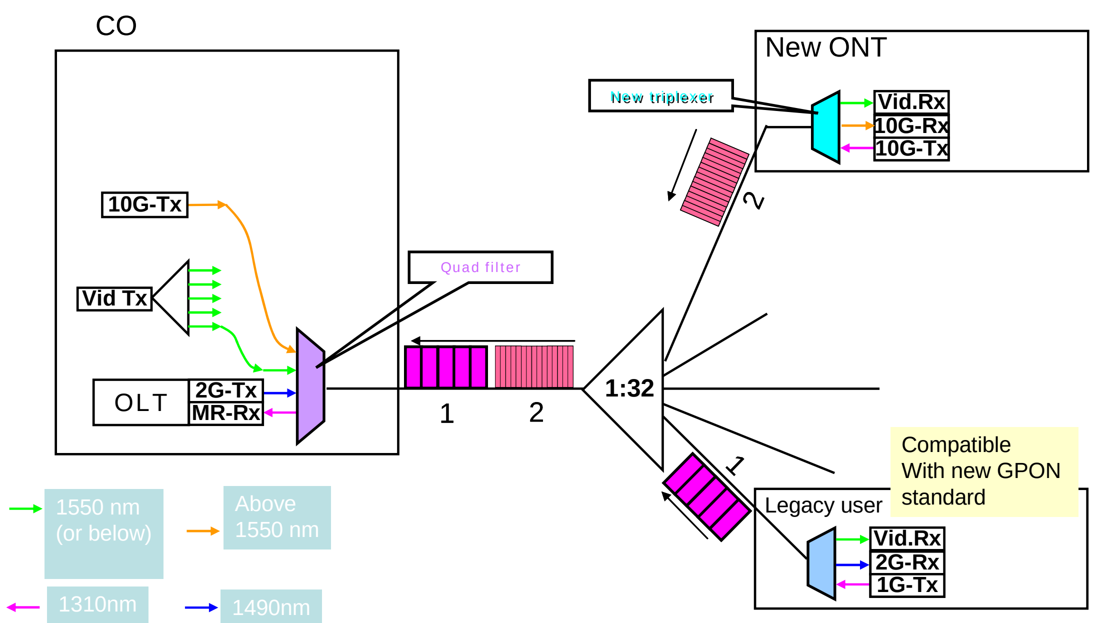


Figure 38: Hybrid TDM/WDM Network

Source: Telcordia

These are the advantages of this approach:

- Graceful transition from legacy, GPON ONTs assumed blind to new downstream wavelength
- Uncooled 1.3 mm ONT transmitter (direct modulation)
- Only 1 new wavelength on PON

These are the disadvantages:

- Multi-rate burst-mode receiver operating at both 10 Gb/s and 1.2 Gb/s faces considerable challenges (e.g., greater dynamic range)
- Synchronization issues between new overlay and legacy PON since they are clocked from different downstream signals
- Legacy system interruption in switch to MR-BMR and WDM at OLT

All three of these approaches to upgrading the PON networks (long-reach PON, D-WDM: PON, and hybrid TDM/WDM networks) are under consideration. All three approaches require extensive work to ensure that the standards bodies make the correct choice.

5 The Impact of Future Video Traffic on the Network

The service providers and cable companies are upgrading their networks and offering new content and services. The movement toward high-definition television (HDTV), internet television (IPTV), and video-on-demand (VOD) requires greater bandwidth and poses new challenges. Operators are addressing the access points using different technologies such as ADSL, Ethernet, BPON, and now GEPON.

Today's routers rely on flow-based hash mechanism to manage packet switching. This management of flows occurs at Layer 3. The-flow based hash distribution depends on the traffic characteristics. Table 4 shows the bandwidth and flows for different types of content.

Flow Type	Bandwidth (Mbps)	#Flows/ 10G Link
Raw HD-TV	1 Gbps	10.00
HD-TV (MPEG-2)	13 Mbps	769.23
HD-TV (MPEG-4)	6 Mbps	1666.67
SD-TV	3 Mbps	3333.33
Video Confrerence	384 kbps	26041.67
VoIP	32 kbps	312500.00

Table 4: Bandwidth and Flows for Different Television Formats

Courtesy of Cisco Systems: K. Wollenweber – OIDA 100 GbE Forum

As the number of active flows that can be supported per link diminishes, the flow-based hash mechanism cannot guarantee equal distribution of the traffic load. The actual effectiveness of the load distribution depends on the hash algorithm, the number of flows, and their size and diversity. With an unequal load distribution, an under-utilization of available capacity can occur, causing artificial congestion, packet loss, and stranded bandwidth. Aggregation of low speed links, e.g., 10 x 10 Gbit/s links, is not equivalent to the 100 Gbit link. As video transmission content increases, networks will require better management of the flows and high data rates at Layer 2.

5.1 Future Video Traffic

Current forecasts for video data show tremendous growth over the next few years. Video streaming (personal and business) will dominate over other content and communication data, and will exert a large impact on bandwidth requirements.

Telecom carriers are considering several architectures for delivery of the video content. Today it is cheaper to store data than to transmit data. Several video architectures assume caching of video on local metropolitan servers. The best configuration depends on the service provider's network and bandwidth. Most companies today believe that Layer 3 requires a 100 Gbit link, 'The Big Fat Pipe.' The principal concerns are stranded bandwidth and ease of management.

Lucent Technologies stated at the OIDA 100 Gbit Ethernet Forum in August 2006 that the actual distribution of content is expected to change significantly over the next 5 to 10 years. The change will necessitate higher data rates in the metropolitan area network (MAN) and will impact the core network. Figure 39 shows the expected demand distribution.

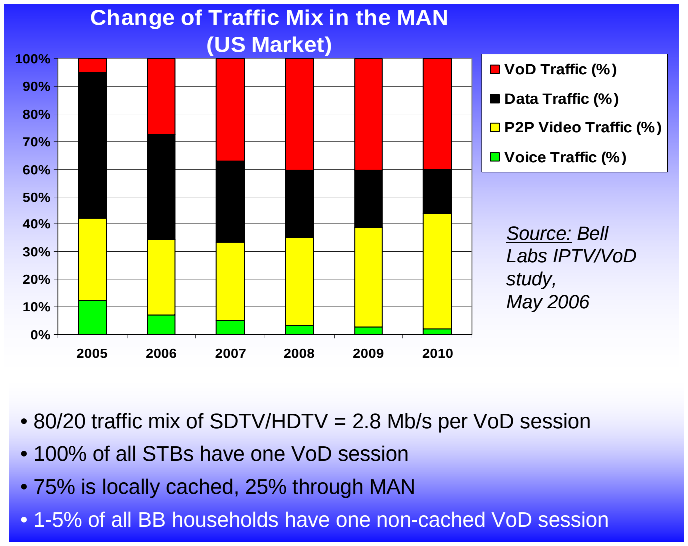


Figure 39: Expected Change of Traffic Mix in the Metropolitan Area Network

Courtesy of Lucent Technologies: M. Zirngibl, OIDA 100 Gbit Ethernet Forum

In reality, the network will need to handle multiple sources of broadband video. User content is increasing. New applications and online social networks, e.g., MySpace, Facebook, and YouTube are generating tremendous quantities of media content. The public networks will have to handle different types of video content, such as IP-based video, broadcast TV, VOD, and mobile video (VCast). (See Figure 17.)

The challenge for the network is to deliver video content from multiple sources over a common infrastructure while ensuring quality of service (QoS). With IPTV, the requirement of minimal packet loss at the TV set is forcing operators to also look at quality of experience (QoE). The customer will demand equivalent quality to that received over the current network.

5.2 Current and Future Network Architectures

5.2.1 Video Content Distribution Today

Consumers connect by satellite, by a cable service, or over the airwaves (the old antenna). As the telecom operators enter the video space to offer triple play packages over their networks, changes are occurring in the network structure. Figure 40 shows two types of broadband access networks deployed today.

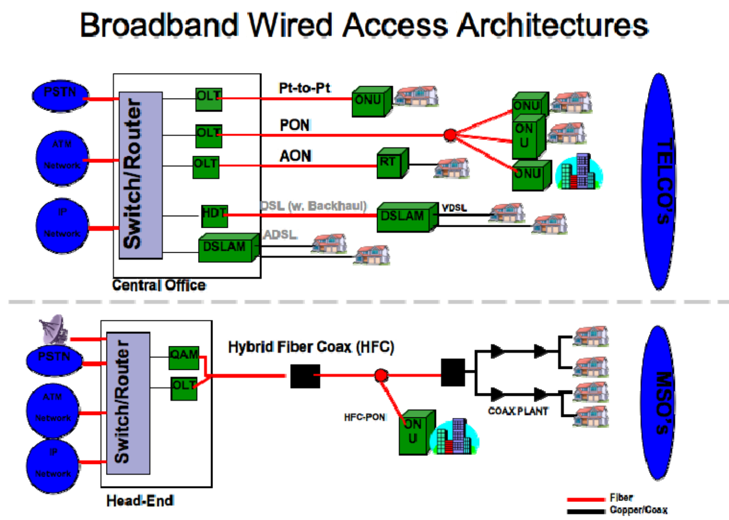


Figure 40: U.S. Multiple System Operator and Telco Carrier Network Infrastructure

Source: Cisco Systems

In the traditional cable TV network, a fiber coax topology controls the distribution and flow of signals. The head end transmits the video signal to a distribution point, where the signal is then retransmitted over the copper network infrastructure to the business or consumer. Fiber is deployed to within 2000 meters of the end user.

Telecom operators are entering the market and offering internet service over the phone lines (DSL and ADSL). They transmit video content via either DSL or a PON architecture such as Verizon's FiOS. Outside the United States, where fiber to the home networks have been installed more rapidly, the PON architecture is more prevalent.

As telecom operators distribute video content with their optical networks, the quality of service needs to remain high, with no loss of signal quality. The latency requirements for IP-V and digital video transmission are restrictive. Table 5 shows the expected video requirements for different services.

Service Type	Minimum Bandwidth Requirement	Tolerable One Way Latency	Tolerable Packet Loss	Tolerable Jitter
VoIP	0.1 Mbps	150 ms	1 %	10 ms
Online Gaming	0.1 Mbps	300 ms	3%	50 ms
Video Conferencing	0.3 Mbps	200 ms	1 %	30 ms
Streaming Video	0.5 Mbps	5 sec	2 %	NA
IP TV	>8 Mbps	300 ms*	< 0.1 %	10 ms

IP TV has by far the most stringent requirements.

*IP TV latency requirement is for channel change responsiveness

Table 5: Video Requirements for Different Services

Source: NGN Report 2005

Video is an important revenue-generating platform for both cable and telecom operators. Revenues from the video content will surpass voice and internet revenues streams. The different modes of delivery (pay-per-view, movie download purchase, rentals and general broadcast) will require different service models.

Figure 41 shows an example of the current multiple system operator (MSO)/FiOS video-on-demand infrastructure. A video-on-demand server lies within the network connected to a broadband service router. The consumer selects a movie to watch from the gateway connection at his home and then orders the movie.

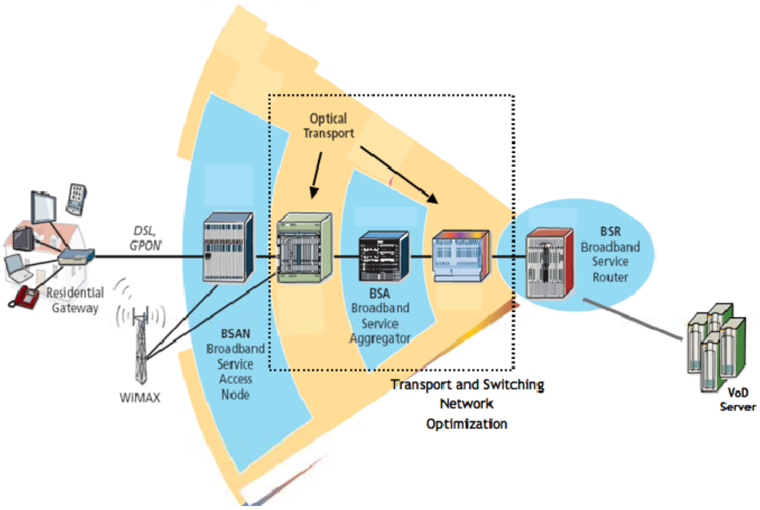


Figure 41: Example of the Video on Demand Server Connection in the Network

Source: Alcatel-Lucent

5.2.2 Dilemma for the Telecom Carrier and Video Delivery

The telecom operator, a new player in the arena, has to determine the point of service access for the video server. VOD services must manage and store a substantial amount of content in movie libraries. The location of the storage facility on the network determines the traffic and bandwidth requirements in different sections of the network (core, metropolitan, and access).

In the telecom carrier architecture, the core network transports information over the wide area network (WAN) and connects to the metropolitan area networks (MAN). The telecom carrier must store the movies for transmission or download on a storage network connected to either the MAN or WAN networks. The carrier can either stream the content from the server to the end user or download the content to a local hard disk in the end user's set top box.

In the case of video streaming, it is necessary to buffer the signal to ensure that packet loss does not degrade picture quality. Vongo, a new provider in this space, offers streaming movie content for a monthly subscription charge.

In the case of video download, the end user connection point needs not only high bandwidth but also error checking to ensure the file content is cleanly downloaded.

The telecom carrier typically stores the content for the service on a video head-end office (VHO) server. More frequently accessed content would then be available at the video hub server (HUB). For the transport, the HUB would distribute content through the central office (CO) location to the access points (consumer). Figure 42 shows an example of this structure.

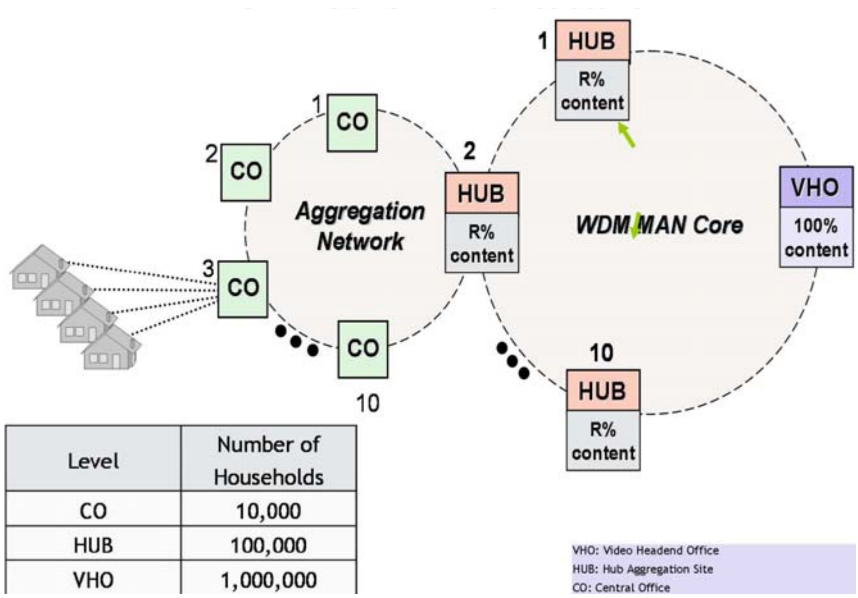


Figure 42: Network Architecture Example for Video on Demand Service

Source: Alcatel-Lucent

A VHO service will provide content to approximately 1,000,000 end users. A video HUB will connect about 100,000 consumers. It's important to optimize the amount of content stored on the HUB relative to that stored on the VHO. If the carrier stores too much content on the VHO, MAN traffic will increase significantly, causing bandwidth bottlenecks and congestion/capacity control issues for the operator.

The simplest way to model the congestion and capacity requirements is to assume a weighted index function with respect to the popularity of the content for download. In the example in Figure 43, a Zipf function is used. It is then possible to simulate the transmission requirements by assuming some fixed percentage of the function is locally cached in the video servers near the central offices.

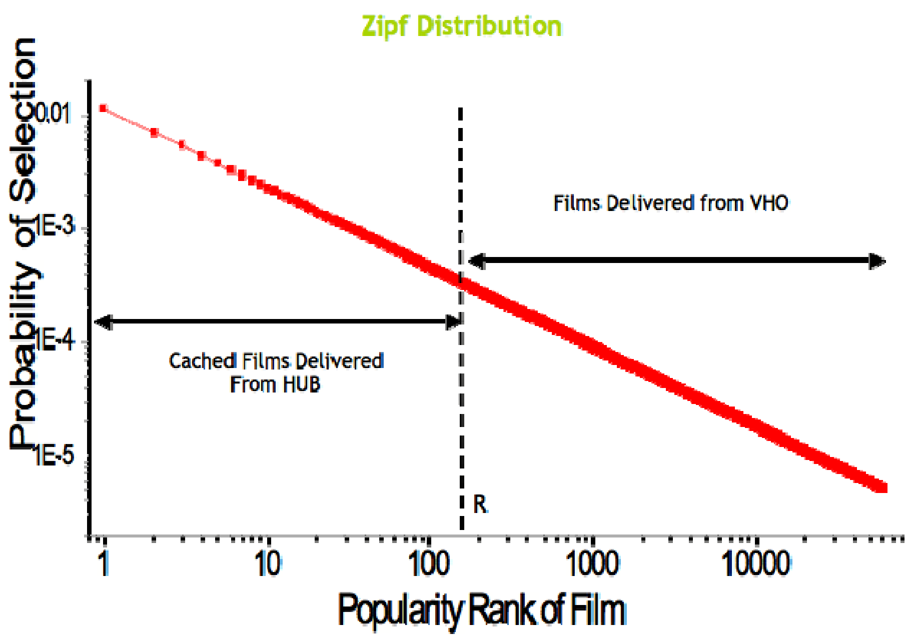


Figure 43: Zipf Distribution for Video Content Profile for Statistical Analysis of Traffic Management

Source: Alcatel-Lucent

The simulations can represent the traffic in terms of Gb/s of transport or as a percentage of the fixed MAN transport capacity. Either approach makes it possible to model the delivery requirements and the number of local video servers that need to be connected to the central offices.

If the VHO server delivers all the video, then the bandwidth requirement increases linearly with the number of households requesting delivery. This would be the worst case scenario; video traffic could quickly saturate the network.

If the carriers cache the most popular films on local servers, the traffic over the MAN decreases (see Figure 44). The replication of the VHO server increases the costs for local

equipment and traffic management. However, it is always cheaper to store bits than to transport them in today's network environment.

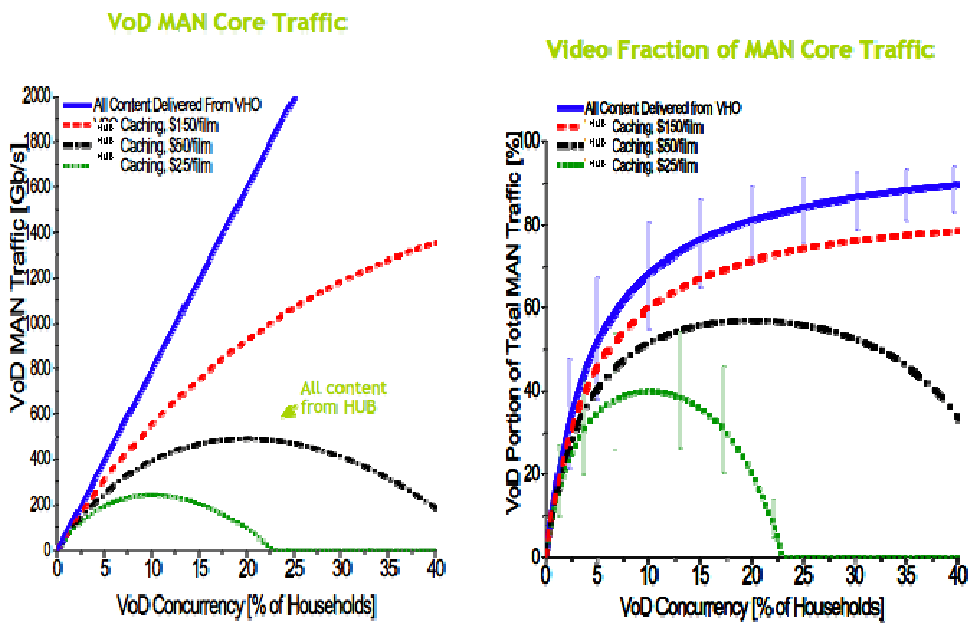


Figure 44: VOD Concurrency vs. Total MAN Traffic as Content Increases on the HUB

Source: Alcatel-Lucent

Standard television distribution doesn't require bidirectional traffic. For the telecom carrier networks, assuming the broadcast introduction point is the WAN, transmission to the network nodes consumes many D-WDM wavelengths. The preferred delivery method would be a single unidirectional wavelength for each central office (CO). This scheme is ideal for an optical drop-and-continue transport scenario. At each CO, the wavelength and information is replicated and sent to each central office in the MAN. Reconfigurable optical add drop multiplexers (ROADM) would easily facilitate this function (see Figure 45). This approach reduces wavelength consumption and allows flexible and remote provision of the service.

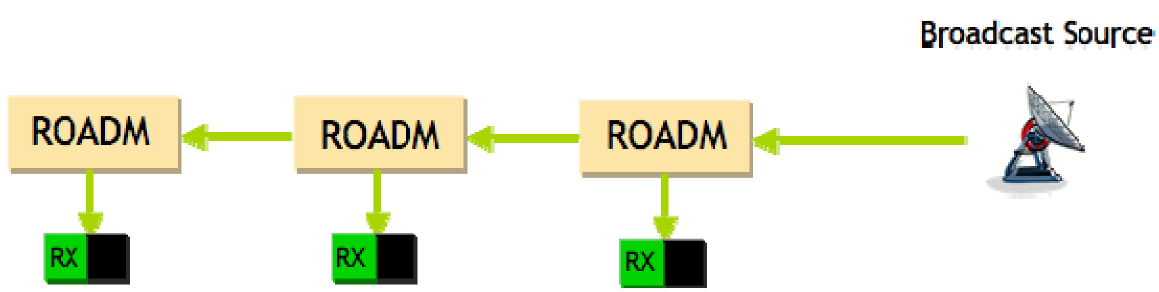


Figure 45: Single-Wavelength Unidirectional Broadcast TV Delivery for Telecom Operators

Source: Alcatel-Lucent

VOD service, on the other hand, requires bidirectional transmission. VOD traffic is user dependent, highly asymmetric, and subject to cycles of peak demand. One potential transport scenario is to use ROADMs for the traffic. In this case, the idea would be to use optical bypass traffic from the video server at each ROADM node. If the content is not required, the wavelength in the metro bypasses the ROADM (i.e., signal not dropped and reconfigured). Figure 46 illustrates this transport scheme.

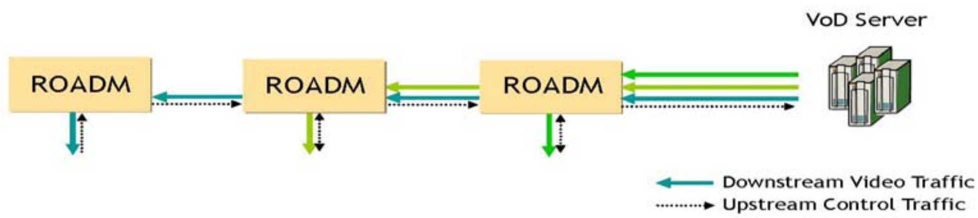


Figure 46: Example Scheme for Video Demand Service for Telecom Operators Networks

Source: Alcatel-Lucent

5.3 Wireless Backhaul

The growth of mobile bandwidth demand and new feature-rich handsets are driving increases in wireless backhaul requirements. The current build out in cell towers is regionally dependent. Asia is the world's largest market for cell towers. Figure 47 shows the geographical distribution of the installed base of cell towers.

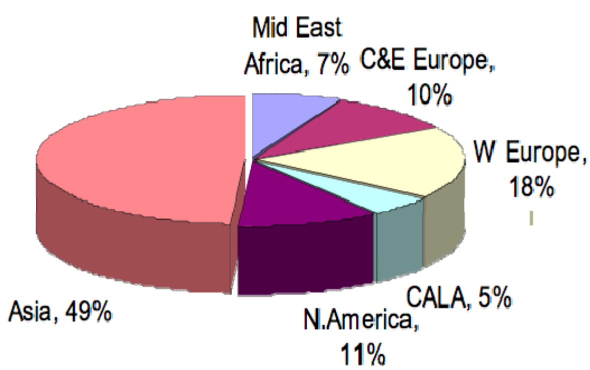


Figure 47: Percentage of Cell Towers by Region of the Global Number of Towers

Source: Light Reading

Wireless backhaul is a key segment of the market for transmission between cell towers over the fiber optic long haul and metro networks. Telecom carriers must decide how to provision and transmit 2 G, 2.5 G, 3 G, and 4 G signals over the fiber network. Several companies using M-PLS and/or potentially Ethernet must maintain low end-to-end delay. Latency and timing recovery are big concerns that must be minimized or eliminated during handoff. Code division multiple access (CDMA) and universal mobile telecommuni-

cations systems (UMTS) are sensitive to differential delay. Global system for mobile communications (GSM) and UMTS are sensitive to timing (≈ 50/16 ppb). The system requires accurate clock recovery and full-path redundancy for failed links.

In North America, T-1 and E-1 lines typically link to cell towers. Figure 48 shows the global share of fiber and copper links.

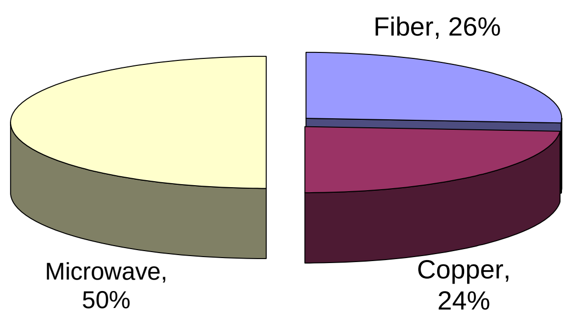


Figure 48: Connectivity of Cell Towers for Offload of the Information

Source: Light Reading

Feature-rich handsets are driving growth in the wireless backhaul market. Both the iPhone and Blackberry are growing in popularity. Figure 49 forecasts the growth in Ethernet connectivity.

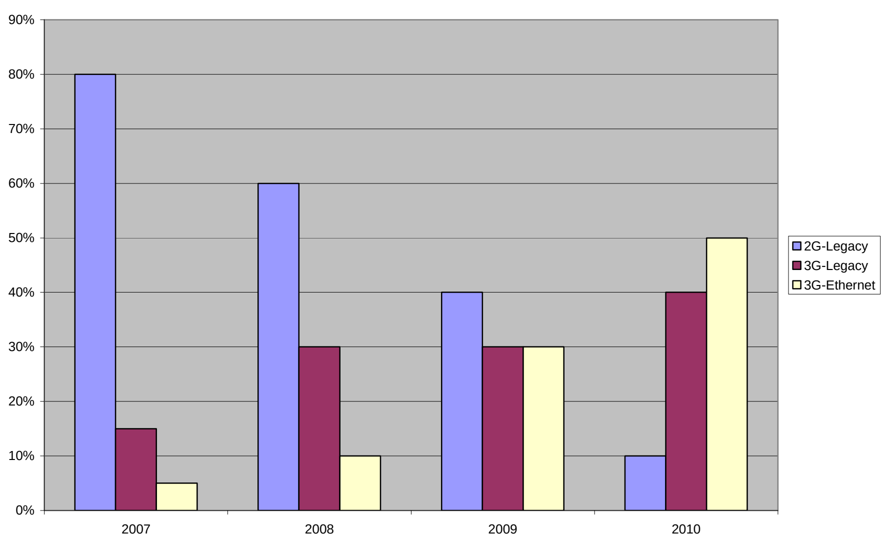


Figure 49: Forecast Shift in Wireless Deployments

Source: Light Reading

Wireless backhaul is a growing market as there is a need to transition from legacy T-1/E-1 lines to Ethernet-based connections. This growth will push 1 Gb/s links to the cell towers and increase the traffic on the fiber optic network.

5.4 Summary

The key concern with current forecast video-on-demand service for consumers is the impact on the traffic management of the carrier networks. If the VHO is the service point for the distribution, then VOD and broadcast television will dominate the traffic across the metro networks. Local caching of the most popular video titles can mitigate this problem. But bandwidth demands are clearly increasing as VOD and broadband network coverage penetrates more residential markets. Successful deployment of IPTV and video services will require skillful management of network resources.

6 Prospects and Issues for Fiber Optic Networks

Global internet traffic has increased at a rate of 75% per year for the past five years. Video now accounts for nearly 30% of all internet traffic and will account for 60% within a few years. These changes have driven widespread deployment of 10 Gb/s links. The industry is installing new network upgrades to 40 Gb/s in the core. Carriers are asking for 100 Gb/s transport in the core to accommodate the growth forecasts. Installations of carrier Ethernet in the metro networks have been increasing rapidly.

Increases in data and flat or reduced cost of services have created an increasing burden for network operators. Telecom carriers have moved into the triple play and quad play arena. The access bandwidth available to users has grown at 30% per year. Verizon has been rolling out fiber to more than 40,000 homes per month. Figure 50 illustrates these key points.

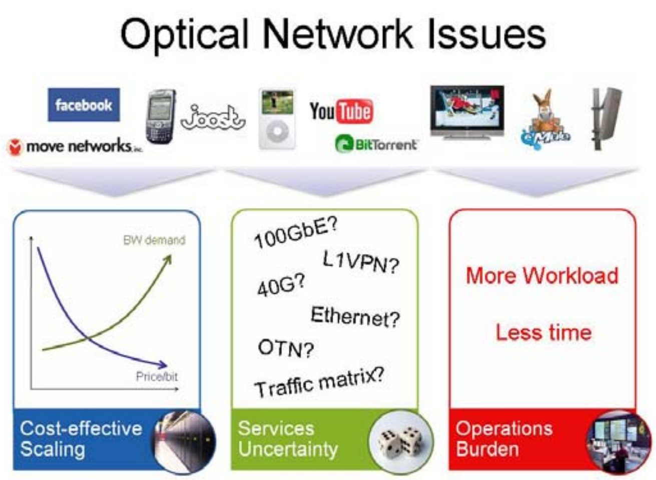


Figure 50: Issues with Today's Network Infrastructure

Source: Infinera

6.1 Service Issues

Today, the business model for the carriers is shifting. Many carriers are both wire line and wireless companies who derive large revenue streams from their wireless plans. Is the wireless handset world moving to the fixed access service fee currently seen for broadband access? Is a flattening or fixed service fee model emerging in communication networks? How will the carrier maintain profitability as bandwidth demand increases? Telecom operators grapple with these questions.

Society has become more connected. The social networking model has changed. Remote storage and peer-to-peer applications are consuming more access bandwidth and creating more demands on the core. As the Internet changes the models for service and social interaction, what new services can the carriers offer?

6.2 Hardware Issues

A related issue is whether to make more extensive use of existing networks or to install new networks, including new fiber. About half the Internet capacity lay dormant in 2002. Today, even though the capacity has doubled, the unused portion has shrunk to 30%. To what extent can carriers rely on dark fiber, or dark wavelengths on lit fiber, to provide a cost-effective response to future network demands?

The answer to this question depends in large part on component-related issues such as desired data rates (and dispersion management), DWDM channel spacing, and fiber characteristics, as well as other upgrade issues such as network management options for present vs. future system platforms that tie to carrier OPEX savings. In any of these network upgrade scenarios, it is necessary to execute the upgrade in a manner that does not disrupt existing services/customers. This requirement can also influence architecture and component selection.

6.2.1 Data Rates

Carriers face a number of issues and options as they move their networks beyond 10 Gb/s transport to 40 Gb/s and 100 Gb/s. For example, the timing and level of deployment of 40 Gb/s systems depends strongly on the pricing relative to 10 Gb/s core network utilization and capacity planning. Telecom companies can select various approaches to data multiplexing, signal encoding, electronic and optical dispersion compensation, etc., applications from data com to long haul. It remains to be seen which of these technologies will be widely deployed. Standards discussions are well underway for 100 Gb/s Ethernet. Numerous approaches have been proposed, each requiring different component advances. In addition, universities and companies are developing technologies for 120 Gb/s systems.

6.2.2 The Access Market

In the access market, prices and connection speeds vary with the country and the operator. The U.S. lags behind several other countries in providing inexpensive access, fiber access, fiber connectivity, and broadband services. The access market has been a bottleneck for bandwidth growth. This issue is being addressed by advanced cable television (CATV) signal distribution networks, new DSL systems, and ever more significantly, by FTTx systems, either as GPON or GEPON deployments based on industry standards. The FTTx systems provide multi-Gb aggregate bandwidths but have very demanding price and volume requirements for optical components such as triplexer transceivers. New suppliers are gaining significant market share.

New FTTx systems, especially GPON, are requiring the deployment of 1-2 Gbps DFB lasers and APDs in quantities at least an order of magnitude larger than past telecom deployments and at very low prices. Suppliers are developing low-cost integrated photonic modules to replace the micro-optic components used today, such as diplexers and triplexers. Each of these advances will have ramifications back to core telecom systems.

In addition, research and standards groups worldwide are investigating future network approaches. For GPON evolution, these approaches include the use of CWDM and/or amplified systems, and for next-generation systems, WDM PONs and long-reach PONs, as well as 10 GbE PON. Each of these advanced architectures has its own requirements for new, low-cost components. For example, WDM-based PONs will require “colorless” transceivers at the subscriber premises (ONU). One promising approach is based on in-coherent injection locking of low-cost FP lasers.

6.2.3 Flexible Networks

Flexible and reconfigurable metro networks are being almost universally deployed, due to attractive features such as remote provisioning and overall lower operating and upgrade costs. From a module viewpoint, this movement is resulting in widespread use of tunable lasers and ROADMs. For each module, there are competing technologies and variants of the product, and several more generations will evolve. For example, ROADMs are now incorporating wavelength selective switches (WSS). Future networks can evolve to all-optical transmission, or islands of transparency, especially for long-haul, utilizing devices such as optical regenerators.

Table 6 spells out one vision for the network requirements of the future. In this scenario, the different segments of the market are based on wavelength switching and mesh architecture. The network would have hundreds of wavelengths in the core operating at 100 Gb/s and be Ethernet capable or Ethernet based.

ACCESS	METRO	CORE
xPON	•40G per λ	•100G per λ
•Per Premise:	• 100 λs	• 100s of λs
1G – 10Gbps Down	• Mesh	• Mesh
10-100Mbps UP	• >1000km reach	• > 4000km reach
• Flexible BW allocation	• Ethernet Capable	• Ethernet Capable
• Ethernet Centric	• Packet Enabled	• Embedded Grooming
• >20km reach	• ADM on a λ	
Enterprise	• Uni-directional Optics	
• 10Gbps λs	• Optical Broadcast	
• Ethernet EPL & EVPL		

Table 6: Network Requirements of the Future

Source: Cisco Systems

Problems with the All-Optical Network

Some contenders view the all-optical network as inefficient due to several concerns, including the following:

- Wavelength congestion
- No sub wavelength grooming
- Service limited by number of wavelengths
- Agility and service provisioning

Figure 51 illustrates several of these limitations.

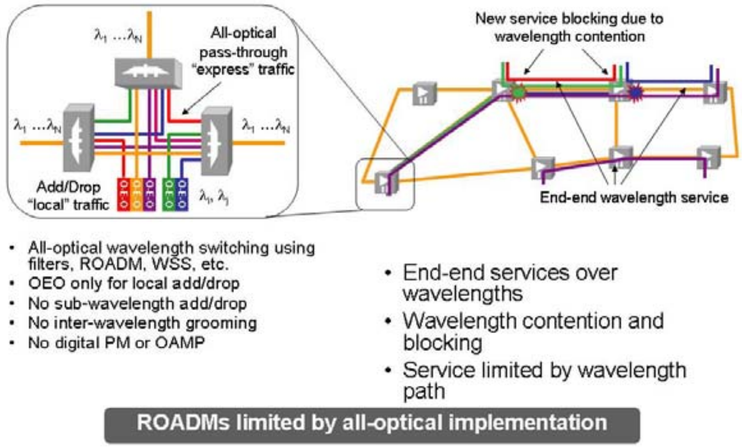


Figure 51: Limitations of All-Optical ROADM and WSS Systems

Source: Infinera

OEO Conversion with Bandwidth Virtualization

An alternate approach to network evolution is to enable low-cost optical-electrical-optical (OEO) conversions and bandwidth virtualization across the network. The concept is straightforward: manage the bandwidth of the network in one control plane and the wavelength transport in another plane. Figure 52 illustrates this concept. The decoupling of the bandwidth service requirement from the wavelength usage allows greater flexibility and prevents stranded bandwidth in the network. By provisioning services electrically at the nodes, we can turn up a 155 Mb/s service, a 1 Gb/s service, 10 Gb/s service or even 100 Gb/s service, without worrying about wrapping different protocol into distinct wavelength on the transport network. Virtualization makes the transport agnostic to the protocol used for delivery.

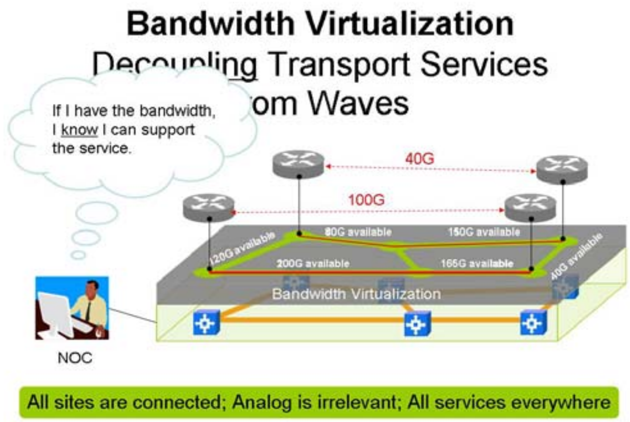


Figure 52: Bandwidth Virtualization Model Based on OEO Conversion

Source: Infinera

In this scenario, a hybrid electrical-optical network makes it possible to access all the network traffic at each node. The concept resembles the current hard disk memory virtualization and software network virtualization ideas for server farms.

Systems using this approach require a significant reduction in the cost of OEO modules. To reduce the costs of OEO conversion, it is necessary to reduce the switch cost by, for example, lower cost line card solutions, more efficient control plane software, and faster reconfigurable networks. One company is currently selling such digital ROADMs and switch equipment. Figure 53 illustrates the concept of the digital ROADM. The digital ROADM resembles circuit switching and provision that the original telecom network providers used. Circuits are established between the nodes on the network. Bandwidth is allocated based on the service requirements between the nodes.

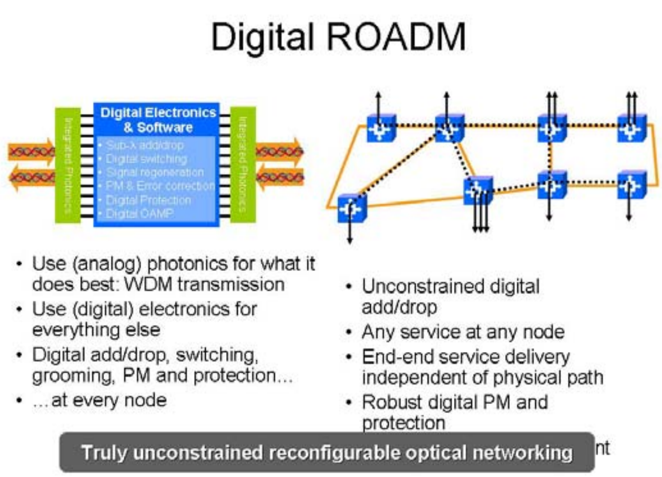


Figure 53: The Concept of the Digital ROADM Based on OEO Conversion

Source: Infinera

The digital ROADM, a hybrid electronic-optical switch, is currently deployed in the network and supplied by Infinera Corp. The switches utilize 10 G lane photonic integrated circuits to enable lower cost line card solutions. The photonic integrated circuits (PIC) have the scalability to enable high transmission speeds as networks come to require advance modulation formats and high capacity links in the future.

6.2.4 The Enterprise Equipment Market

The enterprise equipment market already accounts for about 35% of the overall telecom market. As bandwidth demand grows in the enterprise/datacom/storage arena, there is a premium on key advances in a number of areas, including the following:

- Reusing installed multimode fiber at 10 Gb/s. The LRM standard provides for 10 G transmission over 220 m of MMF, using 10 Gb/s single-mode lasers and electronic dispersion compensation.
- Increasing the transceiver port density on line cards. New form factors such as SFP+ remove some of the power- and space-consuming electronics from the transceiver modules and place these parts elsewhere on the card.
- Migration to 40 G equipment interfaces.

Further growth in enterprise networks will lead to additional component requirements that will push the envelope of performance to ever-decreasing power, volume, and cost.

6.2.5 Coherent Communication

Optical technology is currently about 10 years behind wireless technology in signaling complexity. Coherent communication presents multiple challenges but promises potentially large rewards. Research in this area has proceeded for nearly 15 years.

It is possible to eliminate impairments in signal transmission by encoding the transmitted signal and recovering the phase, polarization, and amplitude with a local oscillator and electronic processing. To achieve coherent detection, we must know the phase, frequency, polarization and amplitude of the signal. Figure 54 illustrates the concept of digital coherent sensing.

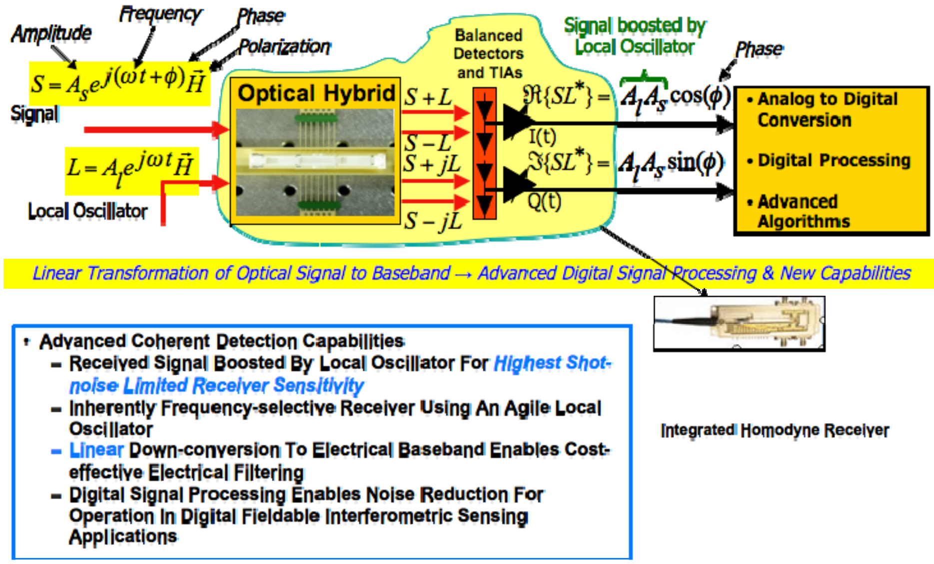


Figure 54: Digital Coherent Sensing Requirements

Source: CeLight

The reconstruction of the signal requires us to view the signal in vector space. The noise or impairment to the signal is then a shift in the vector due to the transmission line. By mixing a local oscillator with the input signal, we can use homodyne detection to reconstruct the signal with adaptive signal processing algorithms. Figure 55 shows an overview of the receiver design for a coherent detector.

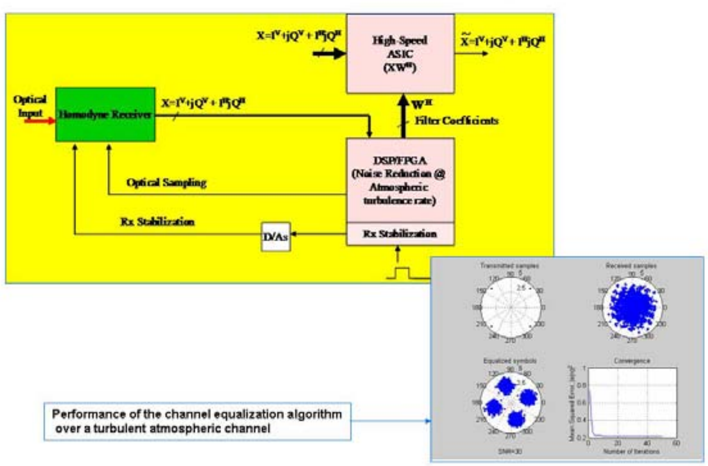


Figure 55: Setup of the Coherent Receiver for Digital Noise Reduction Process

Source: CeLight

In the above example, the transmitted symbols are at 4 point in vector space. The received samples are mixed. It is possible to recover the transmitted signals with adaptive equalization and sampling techniques.

There are advantages in both scalar and vector approaches. By using optical coherent orthogonal frequency-division multiplexing (OC-OFDM), transport systems can move to longer distance transport. In OC-OFDM, data are treated as a *vector* and processed via fast Fourier transform (FFT). OC-OFDM uses the fewest photons/(bit*second*Hz); it approaches the theoretical limit in spectral efficiency. OC-OFDM also offers these advantages:

- Inherent compensation of chromatic and polarization mode dispersion (PMD)
- Inherent tolerance of fiber nonlinearities
- Use of soft turbo-codes
- Optimal for addition to embedded base or new routes
- All-digital OC-OFDM based of FFT processing with no rigid DWDM structure
- Tighter channel spacing than scalar coherent
- Less stringent requirements on analog-to-digital converter (ADC), digital-to-analog converter (DAC) and sampling rates
- One architecture is inherently optimal for any route

At both 40 Gb/s and 100 Gb/s, coherent transmission allows longer transmission distances (6000 km and 2000 km) and high tolerance to both chromatic dispersion (CD) and PMD (see Table 7).

Service rate (Gb/s)	**40**	**100**
Reach w/o regeneration (Km)	Up to 6000	Up to 2000
Modulation	QPSK OC-OFDM	QPSK OC-OFDM
Channel Spacing (GHz)	25	50
Polarizations	2	2
Symbol Rate (G-Symbols/sec)	13	33
- Vector Rate (M-Vector/sec) - OFDM Sub-carrier rate M-Symbols/sec	98	122
PMD tolerance [psec mean]	510	440
Chromatic Dispersion tolerance [pSec/nm]	4900	1550

Table 7: Coherent Scheme for 40 Gb/s and 100 Gb/s Transport

Source: CeLight

It is evident from the number of patent applications being filed on coherent detection and transmission (Figure 56) that interest in this area is gaining momentum.

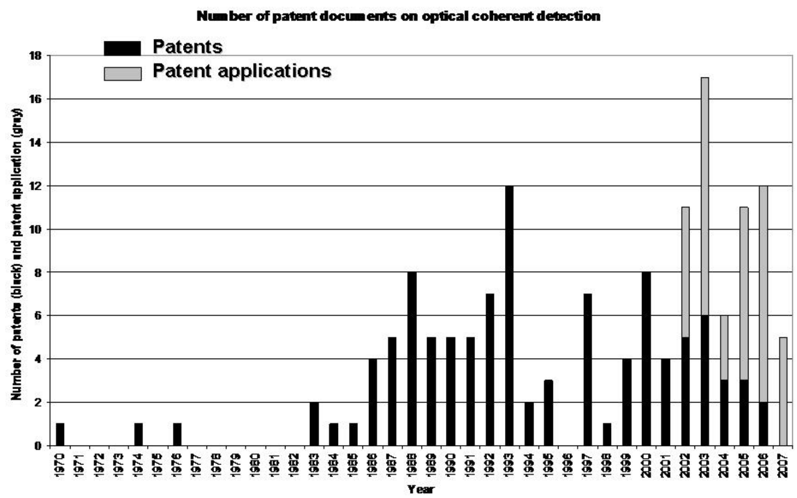


Figure 56: Number of Patents Filed on Coherent Communications

Source: CeLight

There are several challenges in the communication space today. System vendors and component vendors have to deal with changes in business models, research requirements, and product development requirements. It will remain a very interesting space for the foreseeable future.

7 Components for Core/Metro

Today's networks deploy components that were in development just a few years ago. For example, the networks make widespread use of tunable lasers externally modulated at 10 Gbps and of ROADMs with wavelength selective switches for add/drop functionality. These new components enable more flexible and remotely reconfigurable networks that provide enhanced value to service providers. In the coming years, we expect to see less expensive 40 Gb/s sources, smaller transceivers, and more complex ROADMs. The competition between different technologies (free space WSS, PLC, etc.) will continue, and is not clear which technologies will prevail.

Companies that previously supplied only components are introducing higher-level products such as optical nodes that incorporate amplification, signal monitoring and dispersion management, all under common software and firmware control. Original equipment manufacturers are outsourcing circuit packs and line cards.

Electronic and optical compensation techniques and new signal encoding formats have extended the reach of directly modulated lasers (to >100 km at 10 Gb/s) and will allow the adoption of 40 Gb/s transmission on systems designed for 10 Gb/s. These compensation and encoding techniques will continue to evolve rapidly and will speed the adoption of new relatively low-cost transmission systems.

The high interest in 100 Gb/s data transmission is also fueling significant innovation. Component suppliers are developing several parallel approaches such as 10 x 10 Gb/s and 4 x 25 Gb/s as well as 100 Gb/s serial transport technology. The success of 40 Gb/s will depend on the rate at which industry can supply 100 Gb/s components and develop 100 Gb/s standards.

Progress in optical fiber can also affect network design and cost structures. While fiber fabrication is a mature technology, any reductions in loss or dispersion can enable new network build outs which would be future proof as technology develops. Progress in photonic crystal fiber could lead to all-fiber devices (e.g., compensators) and, over the long term, to ultra-low-loss fiber. In recent years, carriers have deployed low water-peak fiber, creating a network that is more suitable for CWDM systems.

This section describes some of the developments in core and metropolitan area network devices and components.

7.1 Line Cards

Carriers have responded to the growing demand for bandwidth by deploying 40 Gb/s long-haul and ultra-long-haul line cards and transport systems. To achieve 40 Gb/s transport on the current core network, the systems must be able to transport the information over distances of 1000 to 3000 km without excess degradation of the signal-to-noise ratio or bit error rate. Long haul transport relies on dense wavelength division multiplexing (D-WDM); i.e., single wavelength transmitter technology. To achieve the transmission dis-

tance, the industry has begun to exploit multi-level encoding and polarization dispersion compensation. For the current 40 Gb/s transport systems, the line cards must be configurable and reliable, and they must include functionality. Figure 57 shows an example of a line card employed in transport systems in the market today.

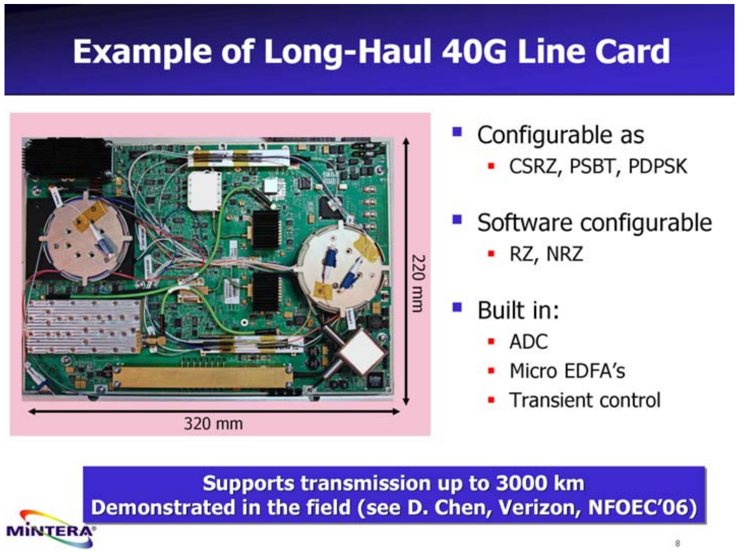


Figure 57: Example of a Line Card from Mintera in Production for 40 Gb/s Systems

Source: Mintera

The 40 Gb/s transport line card systems will evolve toward lower size, weight and cost. Both standard chassis and custom circuit pack solutions are sold today. The ever-increasing need for reduction in size and cost will push the line card solution toward the current 10 Gb/s transponder footprint. Figure 58 highlights this progression.

Figure 58: Expected Evolution of the Current 40 Gb/s Market for Long-Haul Systems

Source: Mintera

7.2 Amplifiers

Optical amplifier technology has replaced electrical repeater systems in the core network, thereby reducing power requirements and complexity. In erbium-doped fiber amplifiers (EDFA), a 1480-nm or 980-nm source pumps erbium fiber to amplify a 1550-nm transport signal. Erbium amplifiers are discrete modules placed at discrete locations within the network. Amplification occurs only within a short length of erbium-doped fiber.

In long-haul systems, telecom carriers are making a transition from discrete amplification to distributed Raman amplification. Typically, a Raman amplifier involves little more than a high-power pump source. The Raman amplifier pumps the signal fiber with high power 1480-nm laser light and provides up to 10 dB of gain with a wide wavelength window (100 nm). Since the source pumps the signal fiber, the amplification is distributed. There is no need to splice or connect the source at discrete points within the transport fiber network. In recent years, carriers have been moving to Raman amplifiers for ultra-long-haul systems and for undersea networks. In undersea networks, Raman amplification makes it possible to eliminate discrete repeaters and to reduce or eliminate power suppliers along the fiber length.

Another advantage of Raman amplification for long haul systems is the link distance that can be achieved for 40 Gb/s system installations. Table 8 shows several calculations of the maximum link distance (in units of kilometers) for various amplification schemes and modulation formats.

Line Technology	Modulation Format			
	PSBT	NRZ-DPSK	RZ-PDPSK	RZ-DQPSK
EDFA	500-600	1000	1200	1000-1200
EDFA + Raman	800-900	1200	2200	1200-1500
All-Raman	1100-1300	1500-2000	3200	1800-2000

Table 8: Link Distance Calculation for Different Amplification Schemes for Modulation Schemes Being Used for 40Gb/S Systems. (Assumptions: 80 Km (21 dB) Spans In SSMF, with Connectors and EFEC. 2-3 Ps Mean PMD, 2-3 dB Deployment Margin, 30 GHz Net Passband)

Source: Xtera Communications

With EDFA amplifiers at discrete points within the network, the maximum transport link distance is 1200 km. All-Raman amplification will make it possible to transmit signals over 3200 km before regenerating them. Raman amplification will make it possible to upgrade future networks for long-haul transmission. It allows full-spectrum use for D-WDM systems on a 50-GHz grid. Several submarine and terrestrial systems are now operating with Raman amplification, including those listed in Table 9.

Year	Operator	Region	Line Systems
2004	FLAG	UK, France	1
2005	C&W UK	UK	2
2006	C&W UK	UK	4
2006	Customer A	Western Europe	2
2006	Global Crossing	UK, Ireland	2
2006	Customer B	Middle East	2
2006	Customer C	Caribbean	2
2007	Customer D	Caribbean	2
2007	Customer E	Middle East	2
2007	Customer F	USA	2
2007	Faroese Telecom	Faroe Islands, UK	5
2007	Customer G	SE Asia	2
2007	Customer H	Caribbean	10
2008	Customer I	Caribbean	12

Table 9: Installation Timeframe and Systems with Raman Amplification by Xtera Corp.

Source: Xtera Communications, Inc.

7.3 Modulation Formats

For the next generation of core networks, the bandwidth and transmission capacity must increase. Currently, 40 Gb/s systems are in deployment. The key concerns with high-bit-rate, long-distance systems are polarization mode dispersion (PMD), chromatic dispersion (CD), and electronic circuit capability.

Traditionally, the best way to increase the transport carrying capacity of the fiber in the core network was to increase the signaling rate (the modulation rate). In 1996, Ciena Corporation introduced D-WDM, which increased fiber bandwidth capacity by transmitting multiple wavelengths (initially spaced at 100 GHz and now 50 GHz) on a single fiber.

As the bandwidth requirements of the core network have increased from 1.6 THz to around 6 THz, the focus has returned to the signaling rate. At signaling rates above 10 Gb/s, the key issues for transmission are the spectral width of the laser source, dispersion management, optical signal-to-noise ratio (OSNR), and PMD.

PMD occurs because a pulse propagates at different velocities along orthogonal polarization axes of the fiber. The PMD is proportional to the differential group delay of the fiber. External or internal strain in the fiber can induce birefringence. At low bit rates, the PMD is minimal and it does not impact the pulse or the maximum distance the signal can travel. However, Table 10 shows that at higher bit rates, the same fiber has higher PMD and can carry a signal over shorter distance.

Data Rate	**Bit period**	**PMD (ps)**	**L (km)**	**L (km)**
	T_B	(Ideal $= {}^{1}/_{10} T_B$)	PMD = 0.02 ps/km$^{1/2}$	PMD = 1 ps/km$^{1/2}$
2.5	400	40	$4\text{x } 10^6$	1600
10	100	10	$2.5 \text{ x } 10^5$	100
40	25	2.5	16000	6.25

Table 10: Distance Limitation vs. Bit Rate for Single Mode Fiber

Source: 100 Gb Ethernet OIDA Forum Report

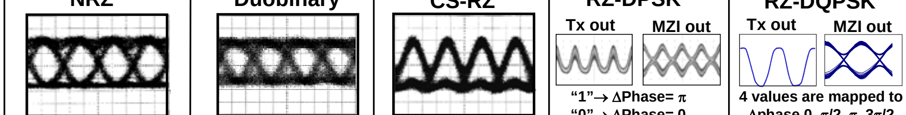
With non-return-to-zero on-off-key (NRZ-OOK) signaling, as the bit rate of the signaling rate increases, the spectral width also increases and the allowable chromatic dispersion decreases, as shown in Table 11.

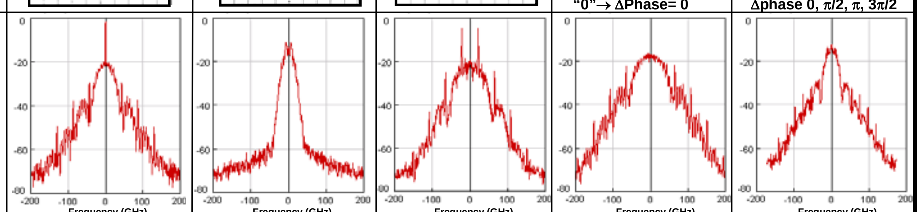
NRZ-OOK	10G	40G	100G
OSNR	15 dB	21 dB	25 dB
CD	±1000 ps/nm	±63 ps/nm	±10 ps/nm
1st Order PMD	35 ps	9 ps	3.5 ps
Spectral Width	20 GHz	80 GHz	200 GHz

Table 11: Constraints with NRZ-OOK Signaling Above 10 Gb/s

Source: Bookham

New modulation formats can reduce the impact of PMD and CD at signaling rates above 10 Gb/s second for single-wavelength sources. As we change the modulation format, we effectively change the bandwidth of the source and the spectral width. Figure 59 shows the consequences of several different modulation formats.





	NRZ	Duobinary	CS-RZ	RZ-DPSK	RZ-DQPSK
				"1"→ ΔPhase= π "0"→ ΔPhase= 0	4 values are mapped to Δphase 0, π/2, π, 3π/2
Optical spectra					
Optical noise tolerance	poor	very poor	medium	good	good
Chromatic dispersion tolerance	medium	good (in linear regime)	medium	medium	good
PMD tolerance	poor	medium	medium	medium	good
Optical non-linearity tolerance	medium	poor	good	good	good
OADM filtering tolerance	good	very good	medium	medium	very good
Hardware simplicity	simple	more complex	medium	more complex	More complex

Figure 59: Signal vs. Spectral Width and Complexity

Source: Fujitsu

The issue of the spectral width is compounded by cascaded optical add-drop multiplexers in the transmission network. The filter response of the OADM causes a problem with the signal-to-noise ratio. Figure 60 illustrates this problem for four different modulation formats.

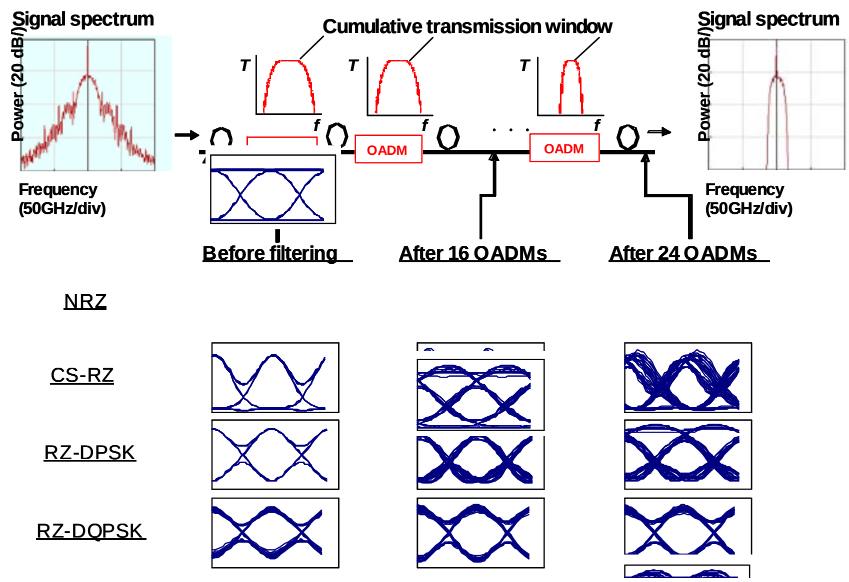


Figure 60: Impact of the OADM Filter Response on the Optical Signal

Source: Fujitsu

The different modulation formats incur different optical penalties. By optimizing the modulation format, it is possible to render the transmission signal more tolerant to the PMD of the installed fiber base and thereby achieve longer link distances without laying new fiber. In fact, the optimal modulation format makes it possible to slot 40 Gb/s line cards into 10 Gb/s transport equipment chassis and thereby upgrade to a 40 Gb/s line rate.

The modulation format determines the complexity of the modulator. As we move to highly complex modulation formats for long haul systems, the material technology and the device construction and design become more important. For current 40 Gb/s transmitter devices, there are several choices for the material system and device design, including lithium niobate Mach Zender devices, electro-absorption modulators, and InP Mach Zender modulators. The increase in complexity can occur at the receiver, at the transmitter, or both. Figure 61 shows the range in complexity from a device perspective.

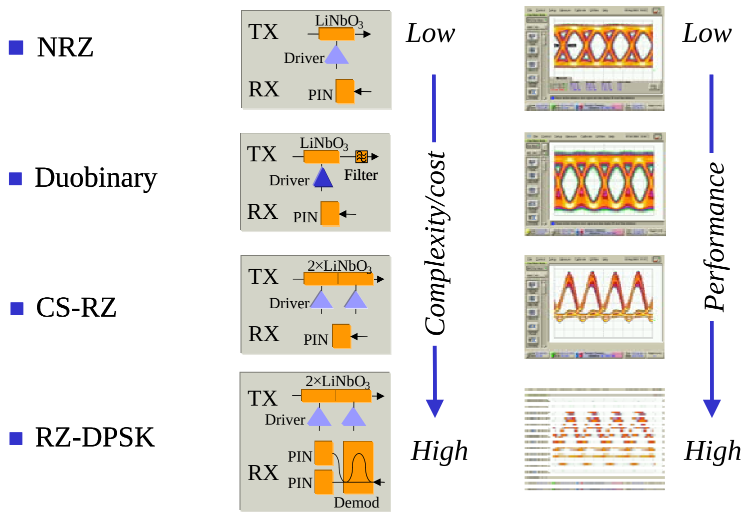


Figure 61: Complexity of Components for Optical Transport Using $LiNO_3$ Mach Zender Technology

Source: Mintera

All the examples assume a Mach Zender as a building block for the pulse generator or pulse manipulator/carver. The non-return-to-zero (NRZ) solution is the simplest in terms of device complexity.

Indium phosphide transmitter technology offers advantages related to integration, size, and power requirements. It is possible to modulate the signal by exploiting the electro-absorption and electro-refractive effects of InP. Figure 62 illustrates the impact on the size of the device:

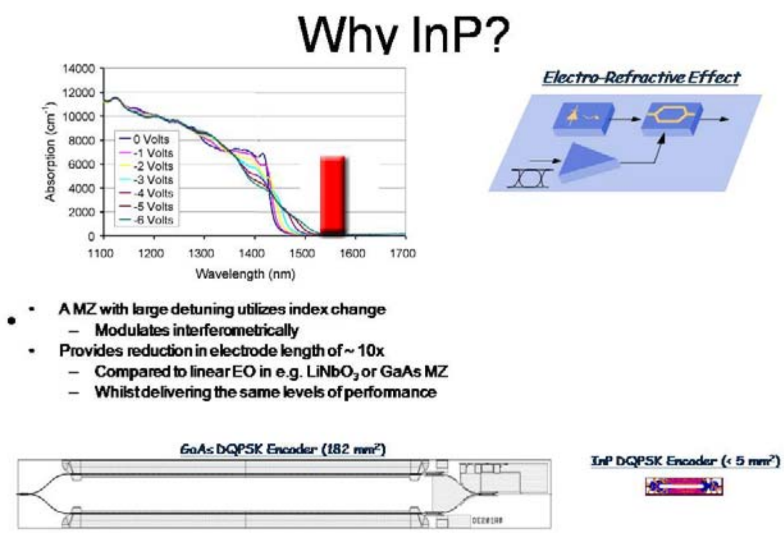


Figure 62: Importance of InP and Comparison of the Size of InP to GaAs DQPSK Encoder

Source: Bookham

To enable the complex modulation formats, several companies propose to integrate multiple functions within a simple transmitter device. The electrical and optical properties of InP have been extensively studied. InP devices are mature. The first strained quantum well lasers were fabricated in 1989. They operate in virtually every telecom network.

Figure 63 shows several reliable InP building blocks. (See also requirements for coherent communications imposed in Table 7 in Section 6.2.5.) Multi-mode interference couplers (MMIs), mode expanders, and deep etch ridge waveguides are well proven for coupling the device functions into a single chip. Low bend loss waveguides can enable small chip sizes and low power consumption at the device level. By coupling the source into multiple Mach Zender modulators, we can generate discrete building blocks for the pulse carvers and manipulators.

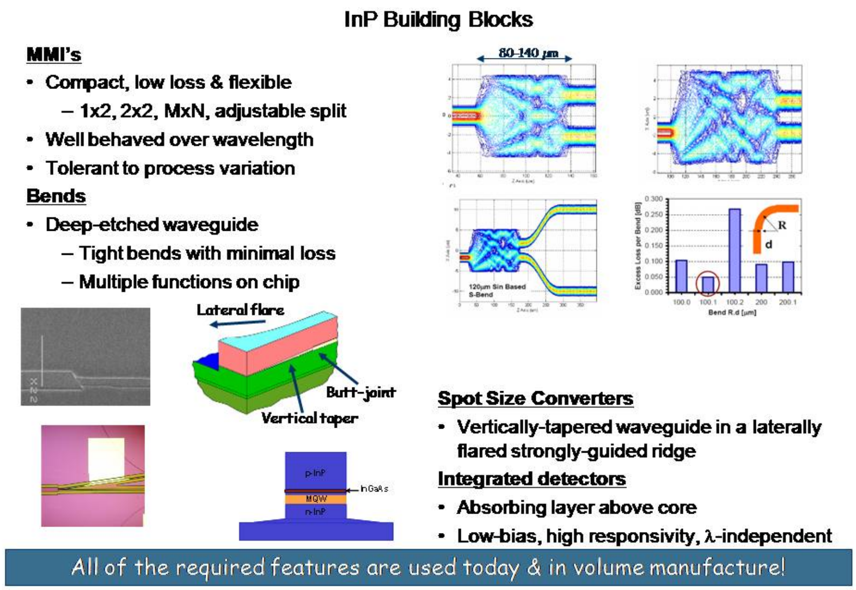


Figure 63: Blocks for Complex Functional Transmitters and Receivers

Source: Bookham

Figure 64 shows an example of the functionality of the building blocks. In this example, two Mach Zenders are coupled to a single wavelength source such as a DFB laser or a tunable DFB laser. The M-Z arms pre-code the data format, which then couples back to the output waveguide.

To control the phase, a $\pi/2$ phase shifter can be incorporated into one arm of the M-Z outputs. A more compact version is shown in Figure 65. On the receive side, delay interferometers can be used in front of the balanced photodiode receivers.

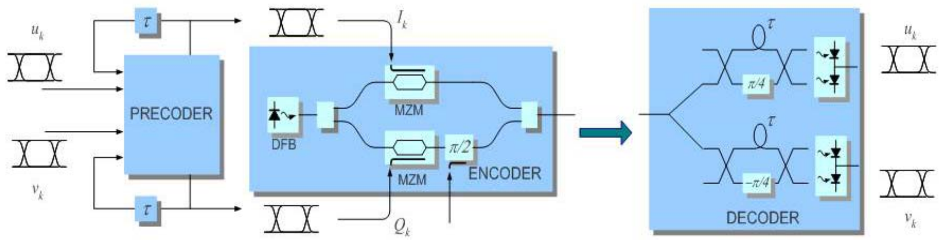


Figure 64: DQPSK Dual Core Transmitter and Receiver Building Block Design Elements

Source: Bookham

The coupling of the light at the end of the transport line can then be decoded in the receiver and the signal recovered.

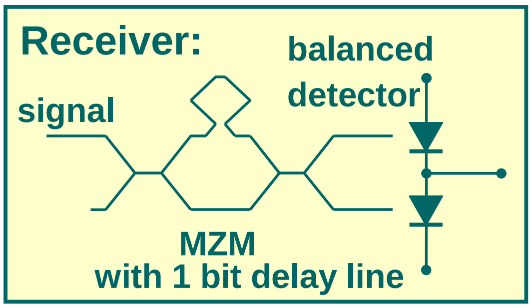


Figure 65: MZM Delay Interferometer in Front of a Balanced Photodiode for DPSK or DQPSK Receiver

Source: u²t Photonics

The encoder chip can be fully integrated within a InP chip as shown in Figure 66.

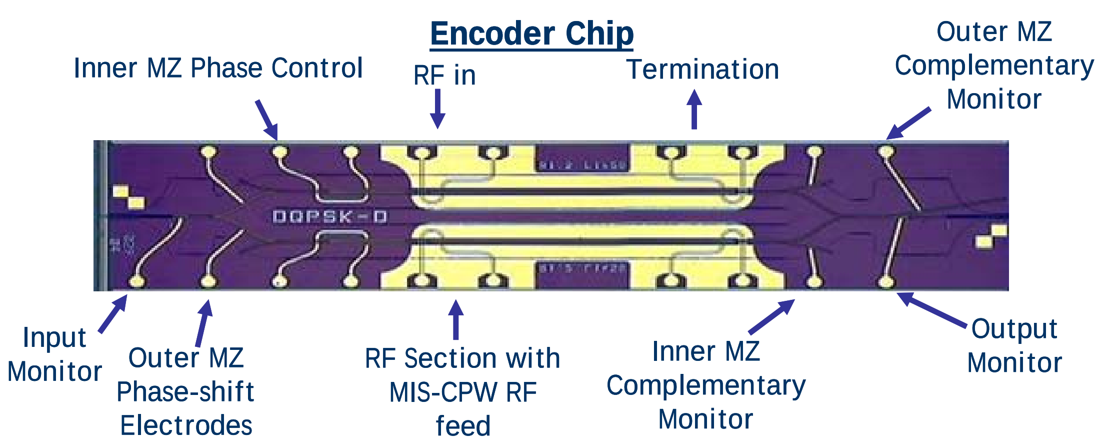


Figure 66: Actual InP Encoder Chip that Can Be Integrated with a Tunable Laser Assembly

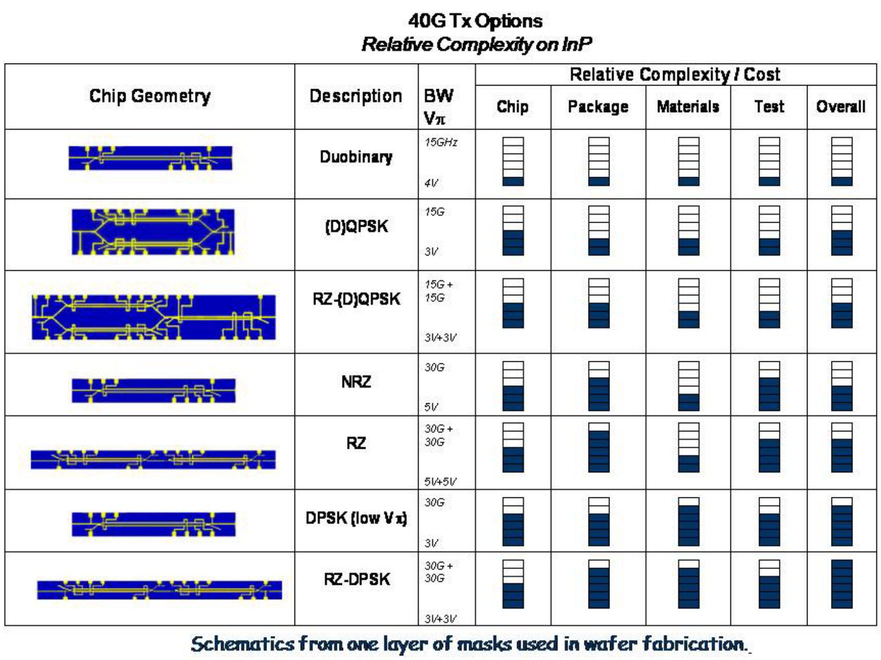
Source: Bookham

The encoder chip, less than 5 mm^2 in size, can be integrated into a standard hermetic butterfly package, as illustrated in Figure 67.

Figure 67: Integrated Tunable DQPSK Transponder Module with Control Circuitry

Source: Bookham

When designing the encoder chips, it is important to assess degrees of flexibility and design complexity. Figure 68 shows the complexity of the different Mach Zender building block integration schemes.



40G Tx Options

Relative Complexity on InP

Chip Geometry	Description	BW V_π	Relative Complexity / Cost: Chip	Package	Materials	Test	Overall
	Duobinary	15GHz 4V					
	(D)QPSK	15G 3V					
	RZ-(D)QPSK	15G + 15G 3V+3V					
	NRZ	30G 5V					
	RZ	30G + 30G 5V+5V					
	DPSK (low V_π)	30G 3V					
	RZ-DPSK	30G + 30G 3V+3V					

Schematics from one layer of masks used in wafer fabrication.

Figure 68: Comparison of Modulation Complexities and Cost

Source: Bookham

In addition to the phase of the light, we can also incorporate polarization control into the transmitter. This strategy increases complexity, but it allows a high degree of encoding on a single wavelength and thereby allows the use of relatively low-speed electronics to

drive the device at 100 Gb/s. The introduction of polarization control into the transmitter design provides the additional option of looking at coherent technology. Coherent transmission can eliminate the impairments that affect the signal as it passes through the fiber. Coherent technology requires digital signal processing, as discussed in the previous chapter. By controlling both the phase and polarization, it is possible to increase the transmission distance of the transmitter and also to eliminate the issues associated with the CD and PMD in the fiber. Figure 69 shows an example of a polarization quadrature phase shift keying (QPSK) core transmitter and receiver.

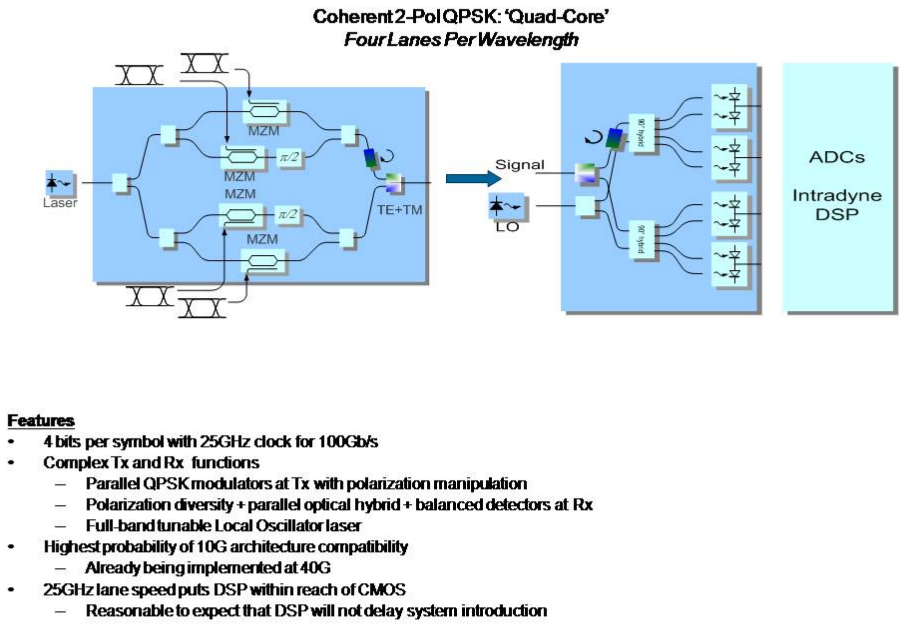


Figure 69: Example of a Coherent Transmitter and Receiver Pair Building Blocks

Source: Bookham

In the coherent example above, 4 bits per symbol are modulated at 25 Gb/s. The aggregate data rate on a single wavelength source is then 100 Gb/s. To control the polarization, one arm of the DQPSK transmitter is rotated by $\pi/2$ to create both TE and TM modes for transmission down the fiber. The DSP on the receiver then decodes the signal to recover it. One advantage of the QPSK building block is that the electronics and M-Z design are well understood at 40 Gb/s for long haul transport. Additionally, each polarization could potentially be modulated at 40 Gb/s, allowing the transmission from a module to reach 160 Gb/s if necessary.

7.4 Fiber

One key reason to move to complex modulation schemes in core networks is the concern over fiber impairments and the installed fiber base. Meanwhile, as line card technology has improved and electronics complexity has increased, fiber technology has not stood still.

7.4.1 Photonic Band Gap Fiber

One of the advances in fiber technology is photonic band gap fiber (or ‘holy’ fiber) shown in Figure 70.

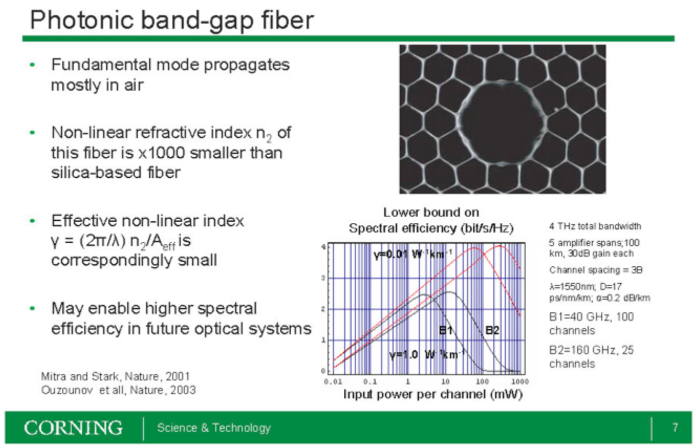


Figure 70: Photonic Band Gap Fiber and the Non-Linear Refractive Index Properties

Source: Corning

The light is no longer guided by total internal reflection. The air gap reduces non-linear refractive index issues and allows higher power transmission in the core of the fiber. This development can potentially allow the use of high power amplifiers. It also increases the spectral efficiency of the fiber.

7.4.2 Nano-Structured Fiber

One new market for fiber is fiber to the home. One of the key concerns for FTTx deployment is fiber management. As we place the fiber in the conduit, the critical concern with SMF28e fiber is the bend radius. With SMF28e single mode fiber, sharp turns can cause bend loss at the turn or potentially crack the fiber and cause a break. To prevent this effect on FTTX deployment, Corning has generated a new fiber cladding called nano-structured fiber. Figure 71 shows the bend loss properties of this new ClearCurve fiber.

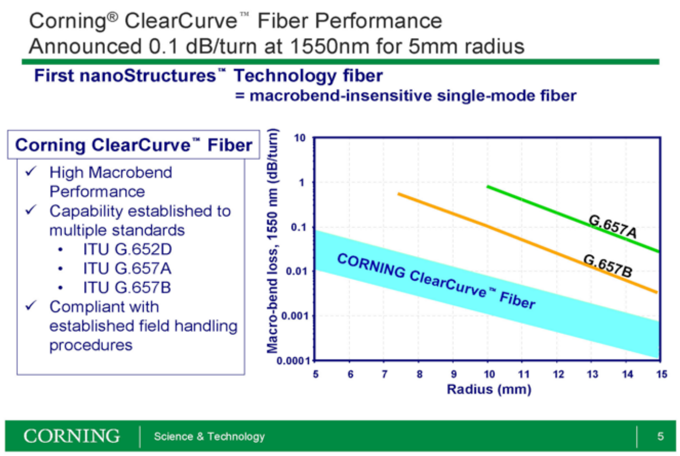


Figure 71: Bend Radius Response of ClearCurve Fiber

Source: Corning

The nano-structured fiber reduces bend loss and so enables FTTx in building structures and apartment blocks.

7.5 Lasers

One route to reducing power consumption of transceivers is to develop lasers which don't require cooling. The initial single-wavelength sources required cooling to assure wavelength stability and power stability over the module temperature range. A typical thermoelectric cooler in a DFB transmitter subassembly can draw 0.5 to 2 watts of power. Micro-coolers which consume less power have been developed for XFP D-WDM transceivers and for SFP transceivers.

In the late 1990s, the first 1310-nm uncooled single-wavelength (DFB) sources were developed. It is difficult to operate D-WDM systems with uncooled lasers because of the requirement for wavelength stability. However, several companies in the chip space are developing technology to move away from coolers to quasi-cooled or uncooled operation. Figure 72 shows the laser technology trend for 10 G transceivers.

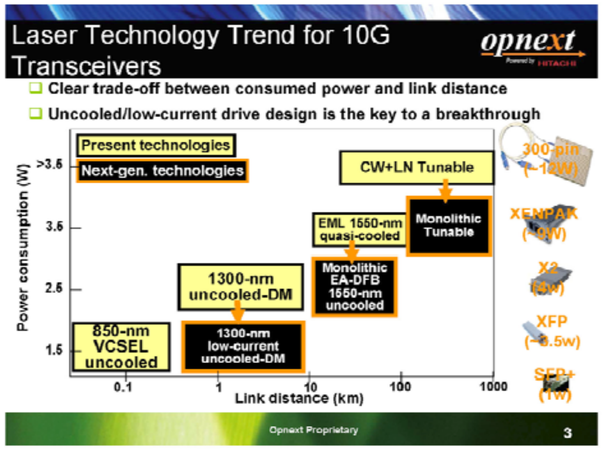


Figure 72: Technology Roadmap for Lower Power Consumption III-V Transmitter Devices

Source: Opnext

Various loss mechanisms inhibit the ability of InP-based devices to operate at high temperatures and to achieve a large modulation bandwidth. These loss mechanisms include Auger recombination, intervalence band absorption, barrier thermo-electronic emission and tunneling, and hetero-barrier leakage.

In barrier thermo-electronic emission, the conduction band of the quantum well laser is low. At high temperatures, the injected electrons can escape, and a population of electronics can reside in the SCH region. This population in the barrier can reduce the modulation bandwidth of the laser and reduce high-temperature performance due to tunneling out of the p-n junction or due to hetero-barrier leakage.

It is possible to improve the modulation bandwidth and high-temperature performance of uncooled devices by changing the material system to reduce the impact of tunneling and leakage currents. We can reduce both thermo-electronic emission and SCH barrier population by improving the depth of the quantum well for electrons. Figure 73 describes some of the material systems which can deliver these improvements.

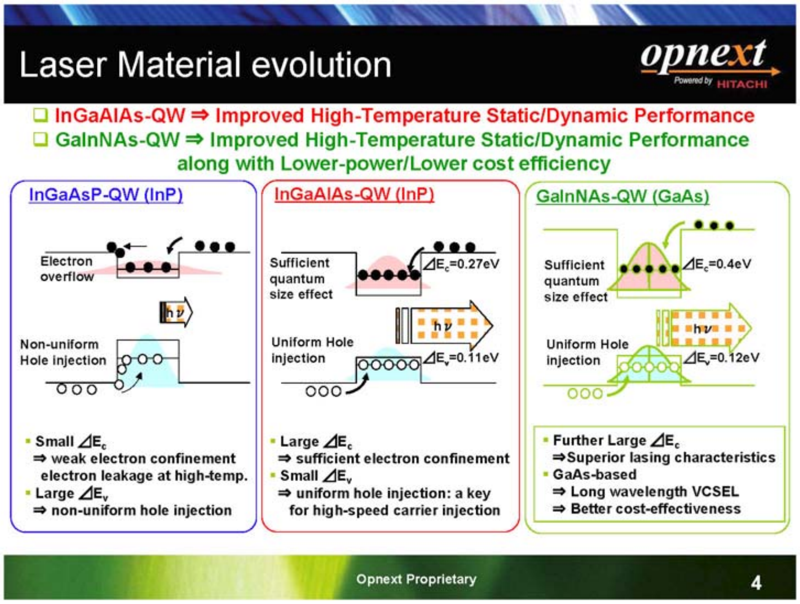


Figure 73: Impact of Material System on the Temperature and Dynamic Performance of Quantum Well Lasers

Source: Opnext

The most common quantum well laser in production is built from the InGaAsP system because sudden failures can occur in material which contains aluminum.

However, InGaAlAs/InP devices can achieve better performance than InGaAsP devices because of the improvement in conduction band offset. In particular, ridge laser designs based on InGaAlAs can match or exceed the performance of buried InGaAsP devices. The modulation performance of InGaAlAs is superior to the InGaAsP devices for an equivalent ridge laser.

Figure 74 shows a hybrid uncooled EA-DFB laser built with butt joint technology. An InGaAlAs modulator section integrated with an InGaAsP DFB improves the modulation and temperature performance of the device.

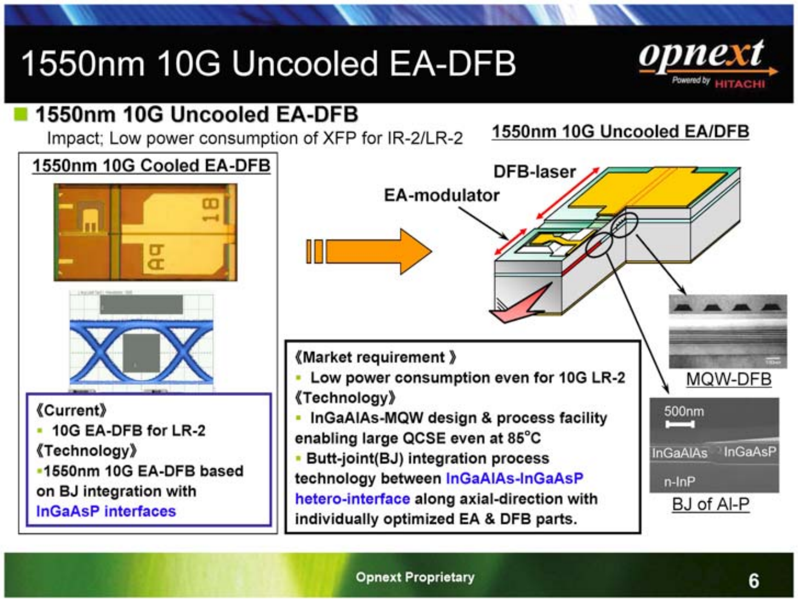


Figure 74: Example of Hybrid III-V Technology for Transmitter Devices

Source: Opnext

The nitride system (GaInNAs) offers an improvement in the conduction band offset even beyond the InGaAlAs system. The goals of introducing the nitride-containing material were to develop long-wavelength VCSELs on GaAs substrates and to improve performance at high temperatures. However, the introduction of nitrogen created problems with the metallo organic chemical vapor deposition (MOCVD) process. To achieve long-wavelength performance, it is necessary to grow the lasers by molecular beam epitaxy (MBE).

7.6 Transceivers

The transceiver combines the complexity of several functions of the discrete transmitter and receiver components into a simple module. Figure 75 shows the evolution of the transceiver package since its introduction in 1992.

Figure 75: Evolution of 10 G Transceiver Package Development since the Early 1990s

Source: Finisar

The Xenpak and Xpak, X2 modules used 2.5 Gb/s input electrical interfaces, while the XFP and SFP+ accept 10 Gb/s line rates directly into the transceiver. Transceivers in smaller packages draw less power because the designers developed ICs that consumed less power and in some cases removed electronic circuits from the module. For example, the clock and data recovery (CDR) electronic chip has been removed from the 10 Gb/s SFP+ module. Figure 76 shows the area and power consumption for various 10 Gb/s transceiver packages.

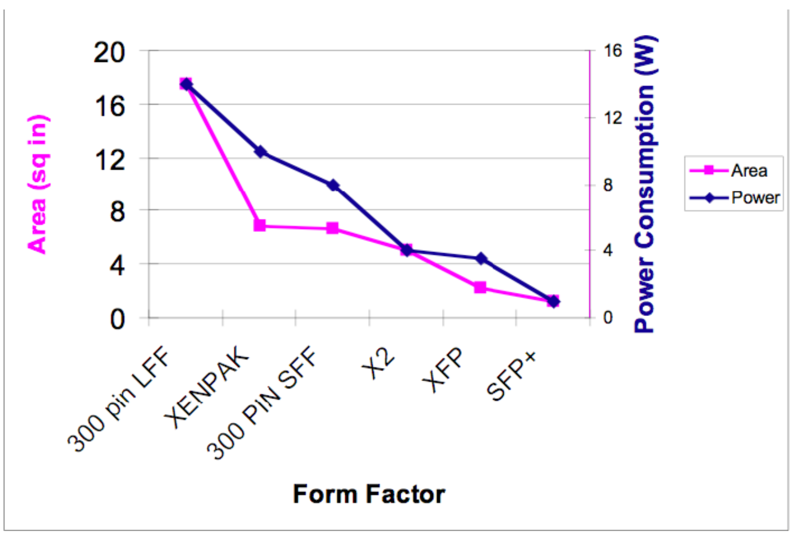


Figure 76: Reduction in Module Area and Power Consumption for Different Form Factors

Source: FInisar

The lower heat load makes it possible to increase the number of optical ports on a line card. Figure 77 documents the increasing bandwidth per inch of line card.

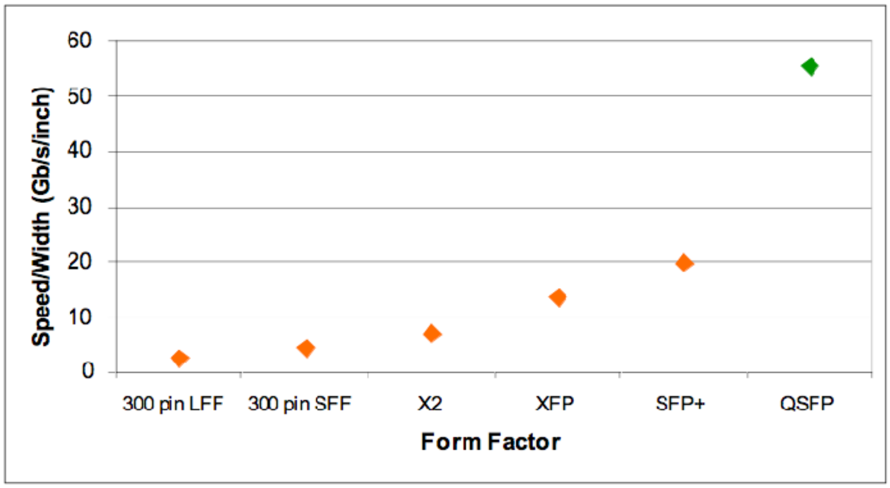


Figure 77: Increasing Speed per Inch of Line Card Width as a Function of Form Factor

Source: Finisar

The market has driven substantial erosion of average selling prices for high-volume, mature products such as shortwave transceivers. The price erosion has created a challenging environment for optical transceiver companies that must generate enough margin to stay afloat and also to fuel research on next-generation products such as 40 G and 100 G.

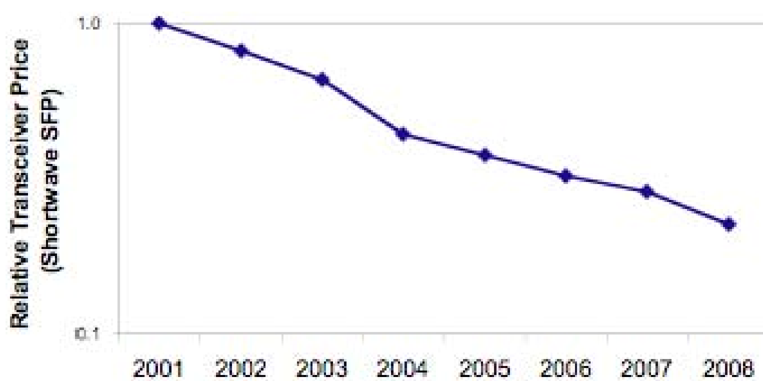


Figure 78: Relative Transceiver Pricing vs. Time

Source: Finisar

To meet the challenging price requirements, some vendors have developed a vertical integration strategy. This strategy can succeed only with high sales volumes.

A fab for optoelectronic chips costs $5 million to $10 million per year, mostly in fixed costs. At 10 million transceivers per year (and 3 chips per transceiver), the fab costs 17 to 33 cents per transceiver. But at 100,000 transceivers per year, the fab costs $17 to $33 per transceiver.

The same argument applies to an IC design group, which costs $2.5 million to $5 million per year.

7.6.1 Ethernet Transceiver Modules

The improvement of III-V chip technology to high modulation bandwidth has a direct impact on the development of the next generation of Ethernet modules. The Ethernet community is developing both the 40 GbE and 100 GbE standard for the metro and long haul market requirements. The maximum distance for the standard for transmission is 40 km.

The improved device performance and modulation bandwidth make it possible to introduce lower-cost 100 GbE and 40 GbE modules for the enterprise market. Some concepts for these modules are primarily based on parallel solutions. It is possible to achieve an aggregate bit rate with 25 Gb/s directly modulated devices or uncooled electro-absorption modulator laser (EML) technology. Figure 79 shows one such proposal under consideration.

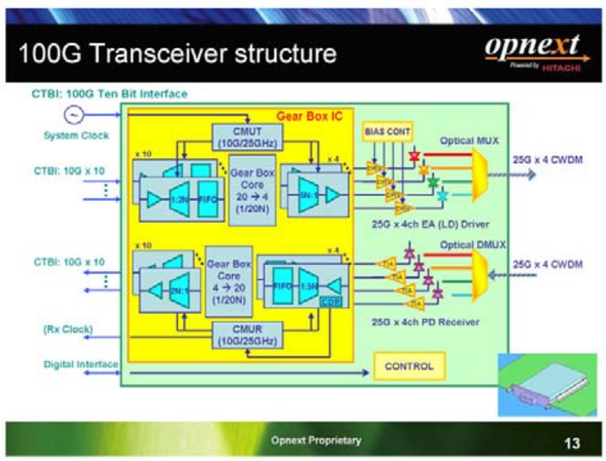


Figure 79: 100 Gb/s module Under Consideration at the IEEE Working Group

Source: Opnext

Next-generation modules will be complex systems which contain new devices. Integration will find a home due to the complexity of the devices required and the impact on packaging. Finally, integration in InP or GaAs-based devices will find an application.

8 Components for Metro/Access – FTTx

Transceivers and transponders are key components in metro, access, and enterprise systems. These devices range from high performance large 300-pin transponders to small pluggable XFP and SFP transceivers for datacom applications. This class of devices has trended toward ever-lower power consumption, size, and cost. Devices at 1 Gb/s are in mass deployment. Most switch and server ports today run at 1 Gb/s.

Since the introduction of C-WDM at 10 Gb/s and recently LRM 10 Gb/s optics, the switch to 10 Gb/s port has been increasing dramatically. The increase in core bandwidth demands and the amount of IP traffic crossing networks, switches, and routers are driving the adoption of 10 Gb/s. With the core networks becoming congested and metropolitan switch ports aggregating 10 Gb/s, the deployment and 40 Gb/s serial solutions have been increasing.

For advanced data communication, the package in development at 10 Gb/s is the SFP+ module. This module removes several of the electronic functions currently found in the XFP transceiver and transponder. The overall impact on the switch or blade is to reduce power dissipation and to increase port count on the line cards.

In the FTTx arena, there is a movement to gigabit passive optical networks (GPON). This trend is placing significant pricing pressure and volume requirements on DFB lasers and APDs to meet the system and power-budget specifications mandated by the International Telecommunications Union. The alternative to gigabit PON is gigabit Ethernet PON (GEPON) which is standardized by the IEEE. In the case of 2.5 Gb/s APDs, projected volumes are at least an order of magnitude larger than historically needed for traditional telecom applications. Meanwhile, for next-generation GPON, there could be a requirement for amplification requiring high performance low-cost semiconductor optical amplifiers (SOA) at both 1490 nm and 1310 nm.

C-WDM PON systems would require broadband amplifiers (e.g., Raman/SOA hybrids). One future PON system, a hybrid TDM/WDM-PON, will require “colorless” transceivers at the customer premises. Several approaches, such as reflective SOAs (RSOA) and injection-locked FP lasers, are being investigated.

The current packages being deployed for the fiber to the home at the consumer/end user access points are triplexers and diplexers. These are the basic requirements:

- 1550 nm downstream – rf overlay for video
- 1490 nm downstream – data
- 1300 nm upstream – data

To integrate the three wavelength requirements into the passive optical network, a multi-function device with 3 ports is required.

Table 12 shows the different PON architecture requirements:

	GPON	EPON	BPON
Standard	ITU-T G.984	IEEE 802.3ah	ITU-T G.983
Bandwidth	2.5G Downstream 1.25G Upstream	1.25G symmetric	622M Downstream 155M Upstream
Split Ratio	1:64	1:32	1:32
Downstream λ	1490 and 1550	1550	1490 and 1550
Upstream λ	1310	1310	1310
Encapsulation	Ethernet, ATM	Ethernet	ATM

Table 12: Overview of the GPON, BPON, EPON Component Wavelengths and Rates

Source: Cisco Systems

Today, the majority of components deployed is based on hermetically packaged components; i.e., transistor outline (TO)-can technology. This package is more than 25 years old. It is used extensively in the communication market segment because of its very low cost. The issue with TO-can technology is that it does not lend itself easily to passive alignment assembly or fast optical alignment automation. Typical process times for semi-auto alignment range from 120 to 180 seconds. The current TO auto assembly equipment uses automatic cap welding, automatic die and wire bonding for both the sub-mount and photodiode components. This approach enables low cost and high volume with throughput on the order of 15 seconds per operation in the build.

Alignment of the parts has traditionally been a slower process. Single-mode alignment depends on high-precision stages and alignment algorithms. A few vendors offer semi-automatic laser welding and some automatic alignment and laser welding equipment for single mode alignment. For multi-component alignment, as found in a triplexer (5 alignments, 49 piece parts), assembly is more difficult to automate. Figure 80 shows the current technology used in the FTTx transceiver module.

Table 13 summarizes the challenges that face future generations of GPON. There are a number of suggested actions aimed at advanced devices that are key to overcoming the barriers; these include developing better and/or lower cost discrete devices such as SOAs and CWDM lasers, and developing lower cost, higher performance integrated photonic solutions.

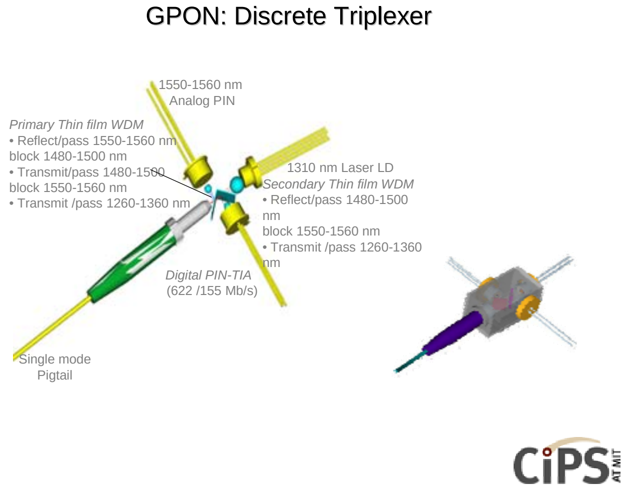


Figure 80: Overview of the Triplexer Technology in Use Today in FTTx Systems

Source: MIT

Technology Challenges: Future GPON

	DRIVERS	BARRIERS	ACTIONS
GENERIC	• Cost reduction • Greater number of users • Lower cost, higher volume components • Forward compatibility - blocking filters - increased address space	• Scaling of discrete components vs maturity of integrated solutions	• Implement cost-effective blocking TFF technology • Low cost, higher performance integration
AMPLIFIED	• Reach extension •Increased number of splitters/customers	•New optical amplifier technology for backward compatibility - 1310, 1490nm	• SOA technology for GPON wavelength plan. Wider temperature • Low cost remote OLT
CWDM	• Overlay additional services and/or PONs	•Tighter wavelength control on lasers (40nm to 20nm) •Utilization of additional upstream wavelengths with maintenance of legacy wavelengths	•Deploy fiber with low 1400-nm loss •Develop low-cost CWDM lasers

Table 13: Challenges that Face Future Generations of GPON

Source: MIT

As the FTTx market continues to grow, the cost pressure on component manufacturers is increasing. To reduce costs and facilitate future upgrade paths, several companies have been developing alternative technology for triplexer components based on silicon photonic or InP photonic platforms. The principal approach is to reduce the assembly complexity of the subcomponent and to reduce the optical alignment tolerance, thereby enabling high throughput and lower cost structures. The photonics platforms offer these features:

- waveguide technology
- wavelength discrimination capabilities
- mode expansion incorporation

- electronic compatibility
- surface mount assembly

Table 14 lists the companies pushing the development and implementation of this approach.

Company	Technology	Intg	Status
NeoPhotonics	Silica PLC; waveguide cplrs	Hybrd	Prod
Xponent	Surface-mount photonics; wave-guide connects	Hybrd	Closd
Enabelence	SOI MZ waveguide filters and planar gratings	Hybrd	Dev
BinOptics	Surface-emitting InP-based photonics	Mono	Dev
PhoXtal	InP waveguides and laser and detector arrays	Mono	Dev

Table 14: Companies Involved in Photonic Platform Integration

Source: MIT

The silicon photonic integration approach being implemented by Neophotonics, Xponent Photonics, and Enablence must compete with the cost structure of the TO-can triplexer. This silicon photonic integration approach uses either silicon or silica waveguide technology. The silica waveguide technology is used in current arrayed waveguide devices and is well understood.

To reduce the cost of optical alignment in the silicon photonic platform, both mode-expanded laser technology and mode-expansion couplers can be employed. Mode-expander technology works well for DFB laser technology, and several different device approaches have been developed over the last 15 years. Figure 81 shows an example of the mode-expanded functionality.

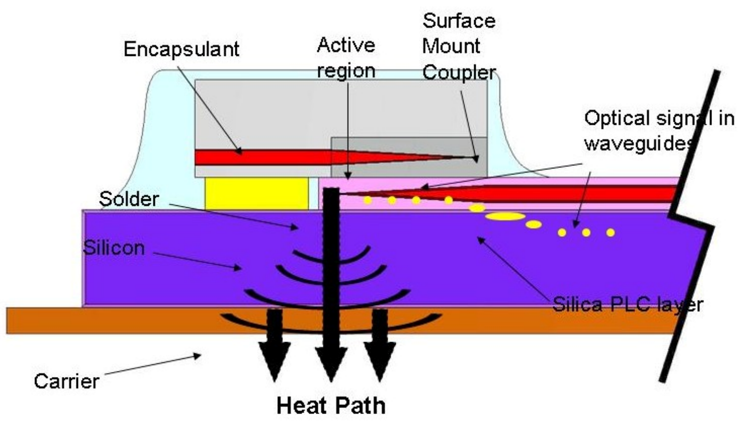


Figure 81: Low-Cost Passive Alignment Based on Silica Waveguide and Surface Mount Technology

Source: Micropackaging for the Next Generation of Optical and Electrical Components OIDA Forum Report

In this approach, the light couples into a silica waveguide as the mode expands from the diode transmitter. Using this approach, high coupling efficiency can be achieved over a wide lateral tolerance of +/- 3 µm. This lateral offset tolerance lies outside the capability of high-throughput surface mount die bonders used in the electronic component sector, where the tolerance is typically 10 µm 3σ. However, it remains well within the capability of the current high-precision flip chip die bonder platforms for optical alignment with tolerances of +/- 1 µm 3σ.

One key issue with the silica waveguide approach is the elimination of the thin film filter in the design for wavelength discrimination. Wavelength discrimination to the receiver components is essential; therefore, it is necessary to assemble a filter onto the silicon platform or to employ a waveguide grating discriminator. This function is relatively simple to implement because the AWG used in D-WDM systems can alter the path length for the different wavelengths and hence pull out the different wavelengths.

Figure 82 shows an example of a silicon platform triplexer. This device relies on a planar grating approach to discriminate between the 1550 nm and 1490 nm transmission paths from the single mode waveguide input. The transimpedance amplifier for the detector circuits is die bonded directly on to the platform. The light from the unit is then coupled into a single fiber input/output port and packaged into a standard footprint package.

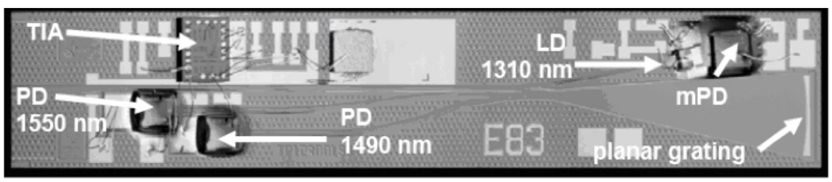


Figure 82: Silicon Platform Triplex

Source: Kotura

As the fiber to the home market expands and the cost pressure on the component manufacturer continues, the technology of integration will provide a more cost-effective approach long term. As the network looks to the next generation of architecture development for high speeds and lower operating costs, the industry will need new products to address wavelength selectivity and to integrate D-WDM into the component space.

9 Photonic Integration

At the component level, a key issue is the rate of progress in photonic integrated circuits (PIC) versus optical-hybrid approaches to provide the functionality needed in future component and systems. For monolithically integrated solutions to be commercially successful, the technology must deliver superior performance and reliability at acceptable prices and performance. Telecom networks have successfully deployed integrated devices such as arrayed waveguide gratings (AWG), reconfigurable optical add drop multiplexers (ROADM), distributed feedback (DFB) laser arrays, tunable lasers, and 10 Gb/s modulators including complex modulators (e.g., DQPSK and duo binary modulators). For PON networks, several companies have been developing photonic integrated circuits to replace the TO-can triplexer module deployed in FTTH systems.

In many cases today, hybrid integration can provide better performance than a photonic integrated device. For example, it is possible to reduce costs and improve yields by co-packaging discrete components such as CW tunable diode lasers and external 10 Gb/s and 40 Gb/ modulators. However, many companies believe a monolithic approach will eventually deliver low-cost, high-performance chip sets, as clearly stated in Figure 83.

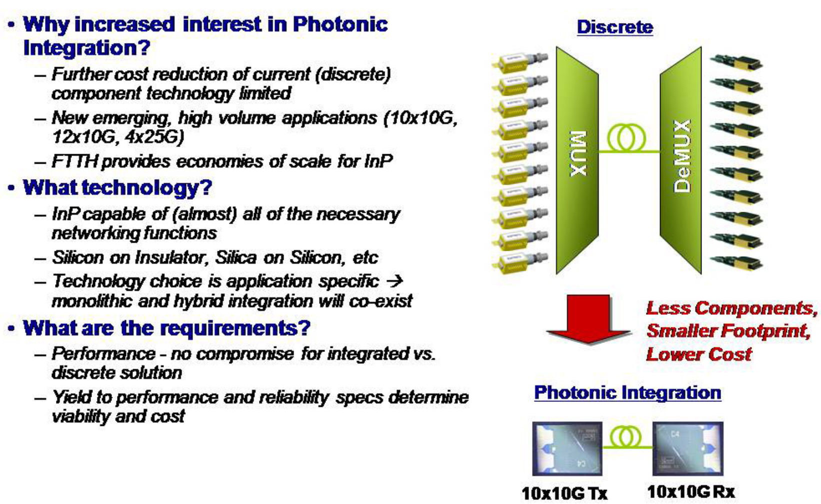


Figure 83: Concept of Integration for Low Cost and High Performance

Source: CyOptics

One of the key successful developments in recent years is the implementation of InP photonic integrated lasers and transmitters for dense wavelength division multiplexing system. One key developer of InP integrated circuits is Infinera, a systems company that leverages its core competency of integration in a digital switch platform. Infinera's approach allows lower cost of ownership for operators of networks due to lower capital investment costs.

To succeed, photonics integration must satisfy several requirements, including the following:

- high yield
- compression of multiple functions into a single device
- scalable connection to both electrical and optical input/output ports
- lower cost of production and better performance
- reduction in power consumption and thermal load

There are at least three approaches to photonics integration:

- silicon/silica hybrid integrated components
- silicon photonic integrated components
- InP fully integrated components

9.1 Silicon/Silica Hybrid Integrated Components

Several companies believe successful integration can only be achieved by a hybrid integration approach, such as fabricating a silicon platform (for example, a silicon or silica waveguide device) and die bonding InP devices (sub-components) to the platform. For example, Figure 84 shows hybrid integration of four DFB lasers with an AWG multiplexer.

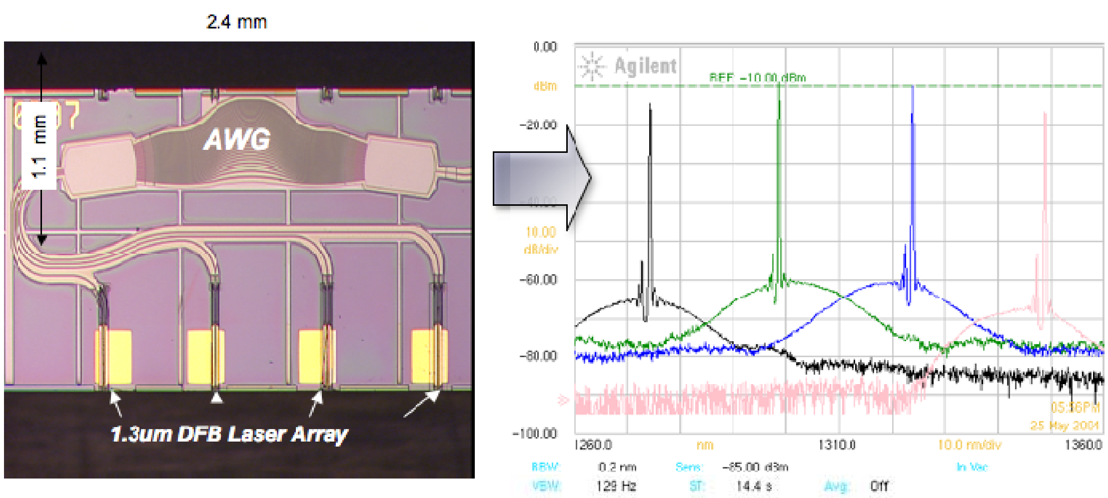


Figure 84: Hybrid Integration of Four DFB Lasers with an AWG Multiplexer

Source: CyOptics

Due to the large separation of the required grating (DFB) wavelength, selective area growth and grating fabrication are unable to provide reasonable yield. Table 15 shows the expected yields for C-WDM sources using arrays vs. single-element devices.

Yield for DFBs

	# Pass	Yield
Single Element	433 / 468	93%
4 Element Array	92 / 128	72%
8 Element Array	33 / 64	52%

Burn-In Yield

	Yield
Single Element	98%
4 Element Array	98%
8 Element Array	73%

⇨ ***4 element arrays more practical than 8 or more elements***

Table 15: Representative Yield Expectation for C-WDM Devices Using Arrays vs. Single Element Devices

Source: CyOptics

Based on the device structure and wavelength requirements, the table indicates that the yield from fabrication and testing decreases rapidly as the number of elements increases.

- For the eight element array, the expected test yield is 52%, while the burn-in yield is only 73%. These figures imply a cumulative yield of only 38%.
- For a four element array, the expected test yield is 72% and the burn-in yield is 98%. The cumulative yield in this case is 70%, nearly twice as much for half the complexity.

In this example, the yield curve is too steep to fabricate complex DFB arrays. Some level of hybrid integration would allow better cost and performance than discrete devices. But beyond some threshold of complexity, discrete devices would be more profitable.

In the hybrid approach illustrated above, it is necessary to address additional performance and integration issues. In this example, discrete DFB devices are coupled to the AWG device. This coupling imposes two new constraints that impact the process yield:

- Coupling efficiency
- Placement accuracy

In fact, both constraints are connected in this example because the InP discrete device has a certain Gaussian far-field pattern and hence coupling coefficient to the single mode silicon waveguide. The coupling depends on both x-y displacement and z-axis displacement. High-accuracy placement equipment is required to control the coupling. Figure 85 highlights the coupling issue.

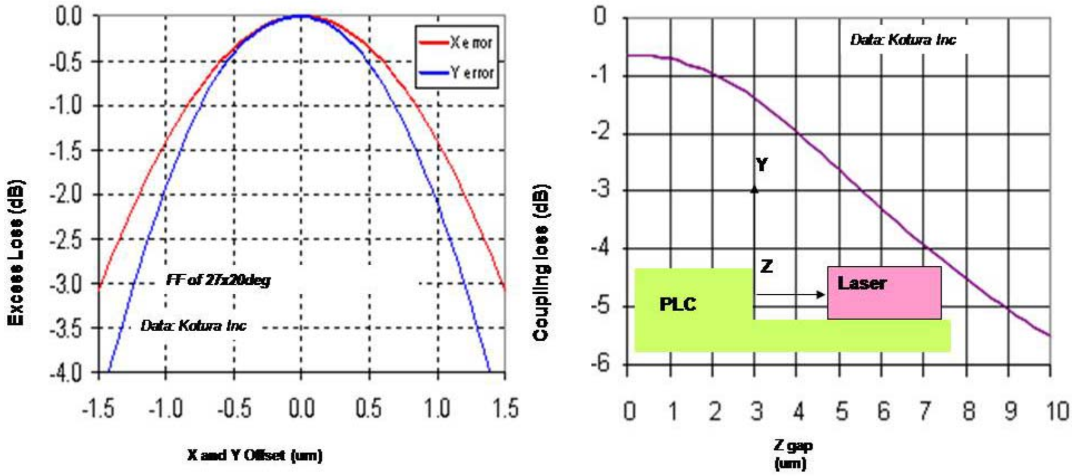


Figure 85: Displacement Tolerance in Both x-y and z for Discrete DFB Component Placed on a Silicon Planar Light Circuit

Source: CyOptics

It is possible to develop complex transmitter and receiver assemblies by the hybrid integration approach. Figure 86 shows a silicon waveguide 100 Gbit transmitter based on using multiple discrete sources.

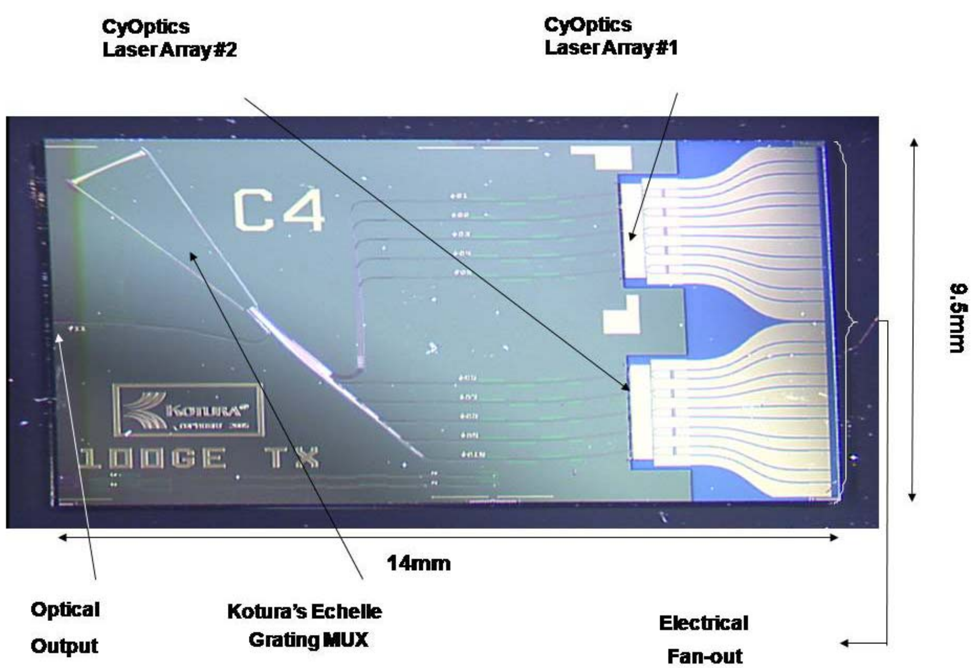


Figure 86: Silicon Waveguide Transmitter Using Multiple Discrete Sources

Source: CyOptics

This approach makes it possible to test each channel independently. Furthermore, we can integrate discrete devices with multiple wavelengths without the constraint of epitaxial

growth control. For example, four DFB lasers with widely spaced wavelengths would require four different grating pitches spaced within four chip widths. A standard holographic grating method could not satisfy this requirement. E-beam writing or phase mask contact printing would be the only solutions. Additionally, performance over the desired temperature range would require selective area growth on a chip-to-chip basis to alter the material gain peak and de-tuning wavelength for the individual DFB laser. This approach would suffer from yield and process control problems. The simpler solution is the hybrid, which relies on proven technology and understanding of chip yield.

The solution demonstrated with hybrid technology enables DFB devices with clean, open eye diagrams and well controlled wavelengths, as shown in Figure 87.

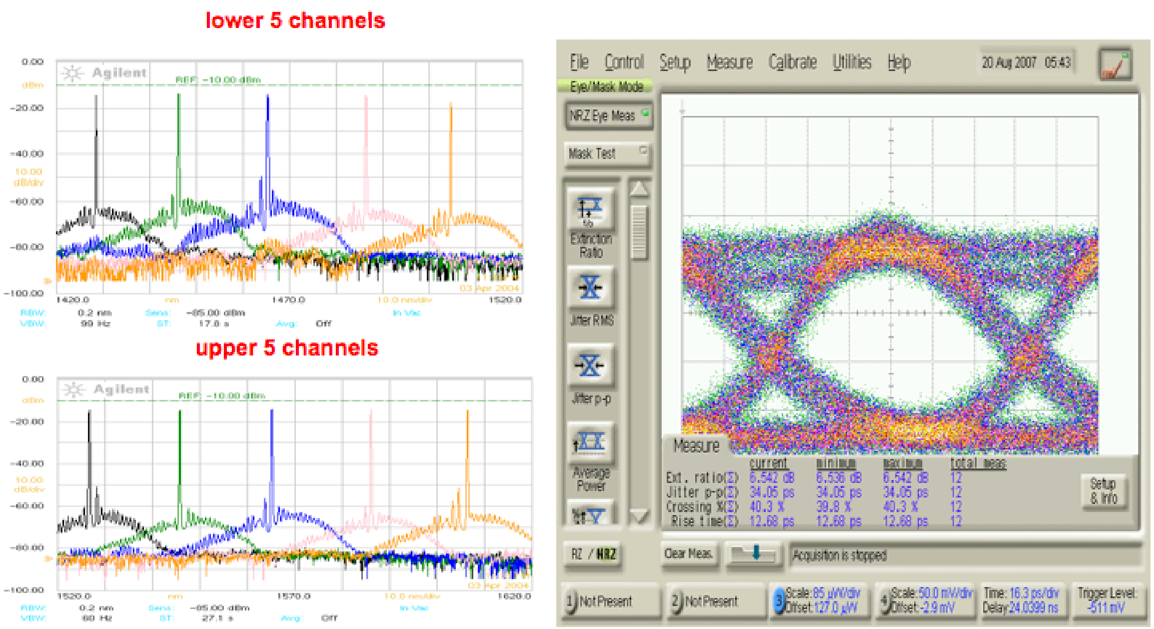


Figure 87: PLC-Based Arrayed Waveguide Hybrid Integrated Transmitter Assembly

Source: CyOptics

9.2 Silicon Photonic Integrated Components

The essence of this approach is to fabricate both optical and electrical elements by complementary metal oxide semiconductor (CMOS) wafer processing. The goal is to marry CMOS electrical processing technology and photonic building blocks. Several companies are investing in this approach as the next logical step in optical integration.

In the CMOS photonics evolution, the idea is to put all the different photonics functions into discrete devices that can then be patterned and processed as individual circuit elements in a CAD design package. One of the leaders in the field is Intel. With the ITRS roadmap suggesting that intra chip interconnects and off chip interconnects will run into bandwidth and signaling limit issues within the next 10 to 15 years, basic research in the

field of optical interconnects is being pursued in Asia, Europe, and North America. Figure 88 highlights the basic six elements of the CMOS photonic process:

- Light generation
- Light guiding
- Light manipulation
- Light detection
- Light circuit integration and assembly
- Light and electronic integration

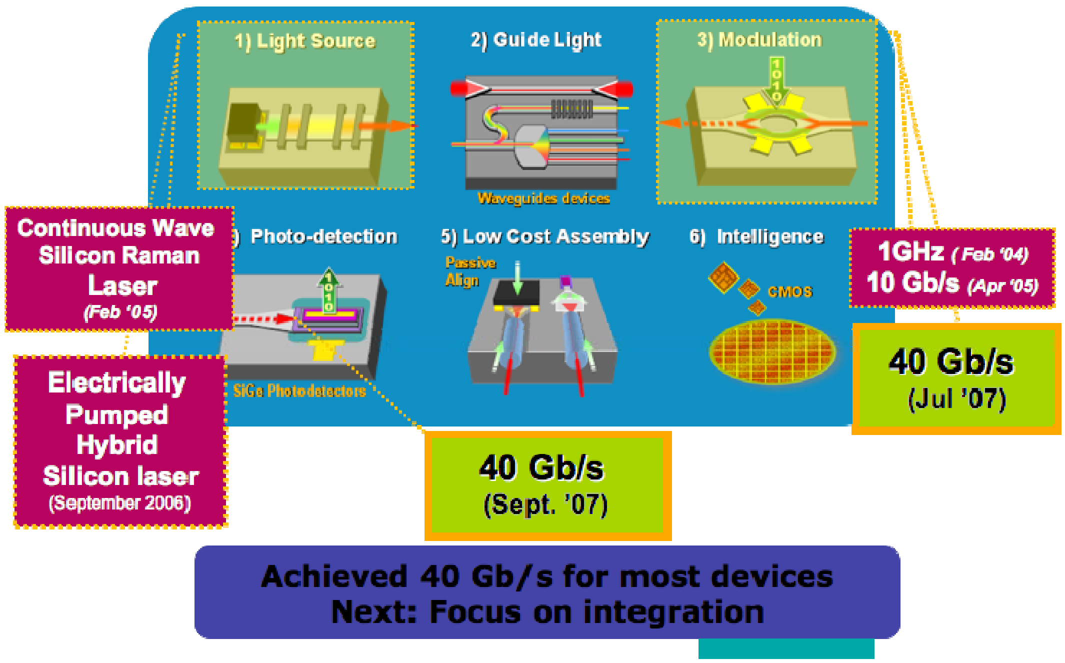


Figure 88: The Six Elements of Silicon CMOS Photonic Integration

Source: Intel Corporation

Silicon is a group IV element and hence has an indirect electronic band structure. The direct transition for a photon to generate light is not allowed. Within the crystal structure, a phonon (lattice vibration) would need to be coupled to a photon transition to generate light. Alternatively, material engineering–i.e., folding the band structure or manipulating the quantum confinement of electrons and holes–is another strategy to generate light (photons). Within Europe and North America, several research groups are investigating silicon light emission. One approach is to grow or implant erbium crystals in the silicon. Another approach is to exploit quantum size effects (silicon/silicon dioxide nanoparticles) to generate gain and hence light within the crystal. (Further information on this is available in the OIDA report *Silicon Photonics: Challenges and Future*).

One advanced approach (apart from laser die bonding to a silicon waveguide) is the wafer fusion device. In this approach, III-V material is wafer bonded to a silicon resonator to provide the light source or photon generator. The silicon waveguide acts as the laser re-

sonator circuit and provides the feedback mechanism to the photon generator to enable gain and hence lasing action. The III-V photon generator is typically InGaAlAs/InP quantum well laser epitaxial material. The characteristic manufacturing step is to fuse a thinned wafer of this material to the processed silicon waveguide resonator. Then an electrical current is applied to the p and n contacts of the devices. Figure 89 shows an example of the silicon resonator laser:

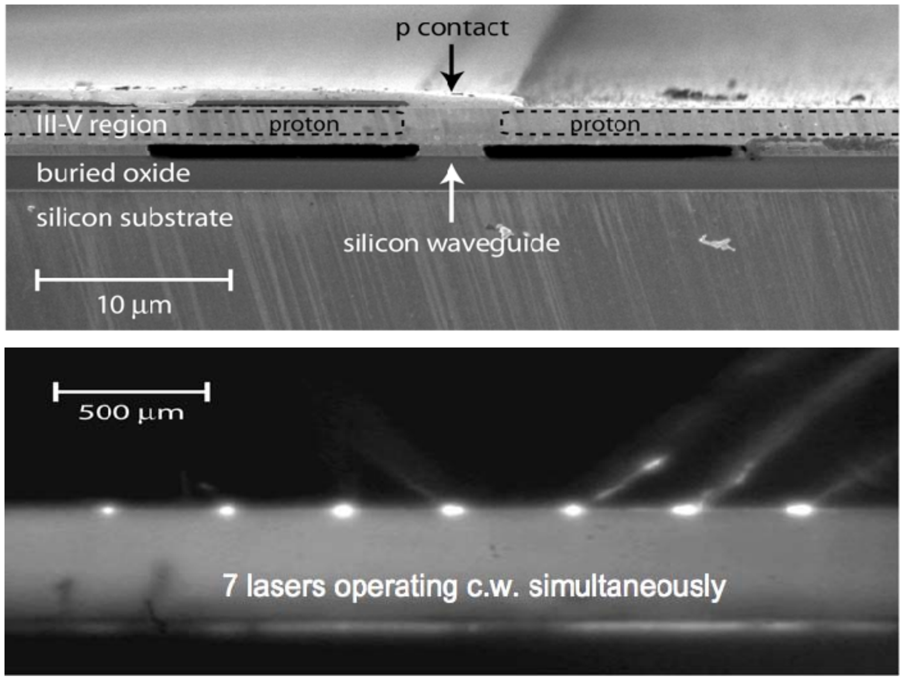


Figure 89: Silicon Resonator Laser Showing the III-V Region and 7 Lasers Operating

Source: Intel Corporation

The principal issue with the wafer bonding process for silicon CMOS devices is the introduction of the III-V material into the fabrication facility or process line. The stringent quality control in most CMOS facilities limits wafer bonding approaches to the end of the process line. Temperatures above 500 ˚C can degrade the III-V material processed on the silicon. (Typical regrowth temperatures for III-V material start at 550 ^{o}C for DFB regrowth and 650 ˚C for standard epitaxial growth. However, phosphorus out-diffusion can occur at prolonged temperatures around 400 ˚C.)

In silicon CMOS photonics, the light manipulator or modulator is directly connected to the light source (laser) by a silicon waveguide. The emission wavelength needs to be below the band gap (indirect gap) of the semiconductor to avoid absorption. Hence this type of device is well suited for long-wavelength communication applications. Today, Intel, Luxtera, and Lightwire are fabricating silicon photonic CMOS devices with 1300-nm lasers. This strategy limits the device applications to long-wavelength transceiver applications, which are dominated by the VCSEL 850-nm transceiver for speeds less then 10 Gb/s.

The waveguide is connected to a Mach Zender (M-Z) modulator fabricated in the silicon as a waveguide, with a phase shifter on the arms of the modulator. The silicon waveguide modulator allows high-speed modulation, but the loss in the guide is proportional to the roughness of the sidewalls of the guide. To alleviate the loss, the manufacturers rely on the high-precision photolithography processes. Figure 90 illustrates the waveguide modulator produced at Intel.

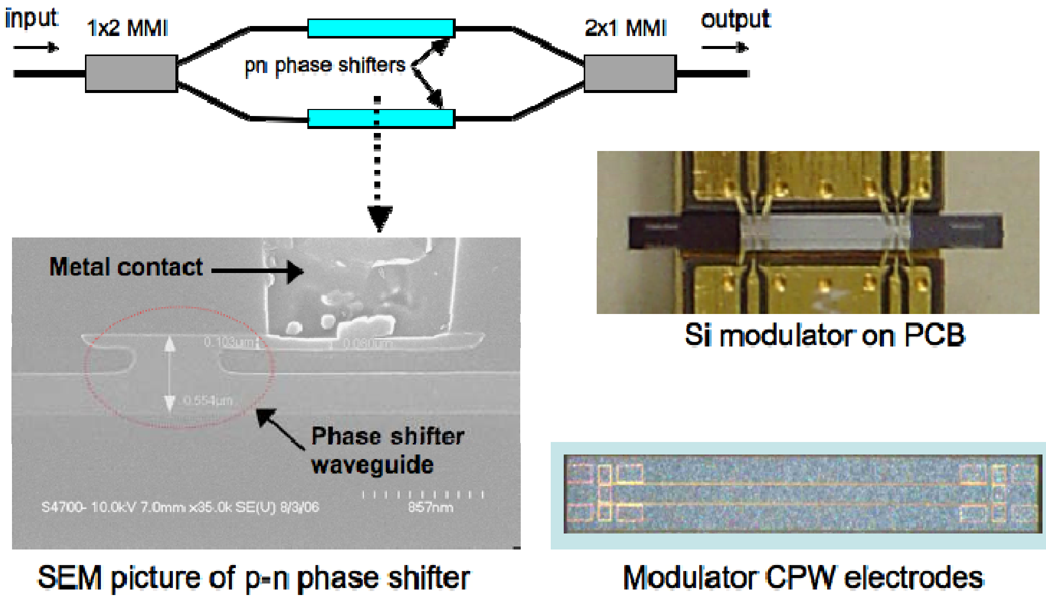


Figure 90: Silicon CMOS High-Speed Mach Zender Modulator

Source: Intel Corporation

The bandwidth of the modulator has been measured as an independent coupled device. Modulation at 40 Gb/s has been demonstrated recently, with further work ongoing to improve the rise and fall times of the modulated signal. The S21 optical bandwidth currently has a 3 dB bandwidth of 30 GHz. This bandwidth is adequate to demonstrate the potential for 40 Gb/s operation, but higher bandwidth would be desired to allow margin for long distance transmission. Figure 91 shows measured performance data for a silicon CMOS M-Z.

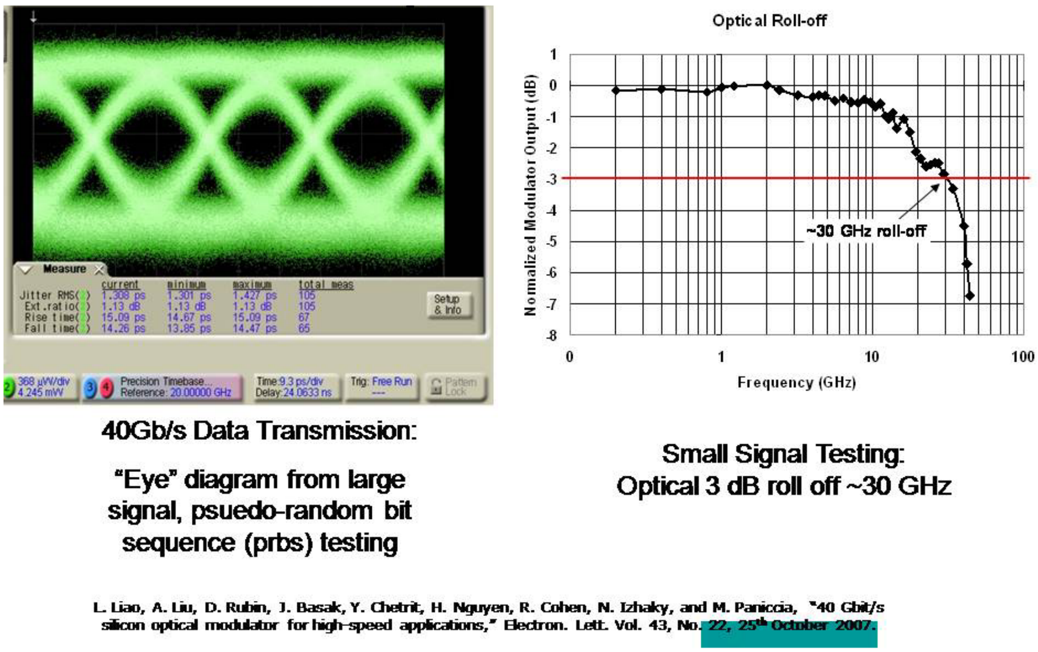


Figure 91: Large Signal Modulation of a CMOS Mach Zender

Source: Intel Corporation

The final stage of the CMOS circuit is to reconvert the optical signal back to the electrical domain. To do this, we need to integrate the photodetector into the CMOS circuit. One of the preferred methods is to use a dopant in the silicon to absorb the received light.

As the light flows in silicon optical waveguides around the opto-electronic integrated circuit (OEIC), a waveguide detector is needed for optimum efficiency. This approach allows simple integration into the circuit process. Germanium has been used extensively in photodetector technology for several years. The conventional approach is to form a receiver by implanting or fusing germanium onto the silicon waveguide and forming a p-n junction to sweep the carriers out of the absorption region. Planar processing of the detector chip simplifies the fabrication process. Figure 92 shows a cross section of a germanium waveguide detector. The p and n contacts are fabricated on the surface of the silicon waveguide, allowing simple wire bond pads to be used for test purposes. An alternative approach would be to use the laser source in reverse as receiver technology, rather than as emitter technology.

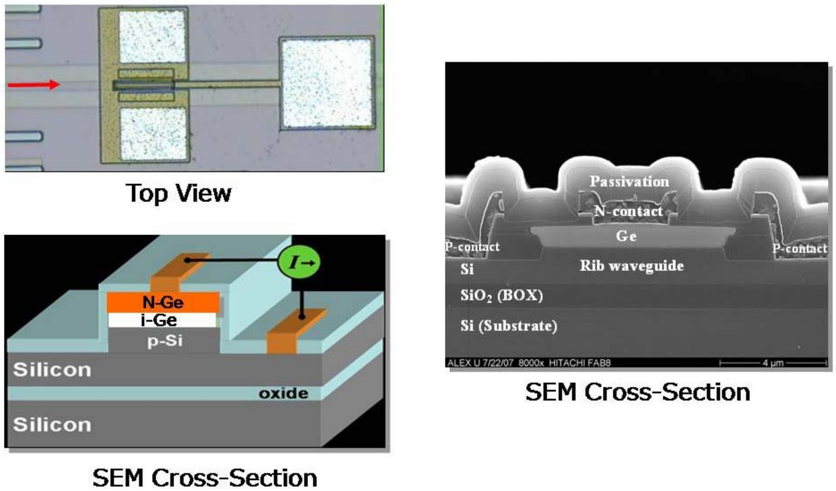


Figure 92: Germanium Waveguide Photodetector

Source: Intel Corporation

The germanium waveguide detector has a bandwidth of around 30GHz. Receiver eye diagrams with 40 Gbit input signals have been demonstrated with low noise on the receiver eye. Further research to increase the sensitivity and bandwidth are ongoing.

9.3 Indium Phosphide Fully Integrated Components

The alternative to the silicon CMOS photonic integration approach is the “pure” InP integration. This wafer process technology begins with an InP substrate rather than a Si substrate. Flip chip bond pads or wire bonds connect the InP chips to the electrical drivers. Silicon-based electrical circuits (CMOS, SiGe) supply the electrical functions to drive the InP integrated device.

InP devices are direct bandgap semiconductors. The light emitting portion of the device is grown in an epitaxial step. The growth of the crystal structure is controlled to within a few monolayers, i.e., several ångströms of thickness. Today, multiple device structures exist. These device structures are well understood and have been deployed in the communications industry for over 20 years. Today, most telecom networks employ InP long-wavelength devices for transmission over the core, metropolitan, and PON networks.

One of the key issues with InP integration is yield. When we integrate multiple complex epitaxial devices onto the same substrate, the yield is a function of both the design complexity and the constraints of the epitaxial structure and processes. In the silicon world, the impact of process control and yield is extremely well understood. In the InP world, the yield has not approached 90%.

Research scientists have explored InP photonic integration for the last 20 years. They have achieved many advances in both the epitaxial integration technology and the waveguide technology. However, several key issues remain, including:

- substrate strength
- incorporation of multiple epitaxial re-growth stages
- photolithography process tools
- computer aided design (CAD)
- applications and cost of hybrid technology

One key difference between the CMOS photonic approach and the pure-play InP photonic approach is the standardization of processes. Within CMOS fabrication lines, standard process control and constraints have led to a successful outsource fabrication business model for electronic components. Within the InP community, the largest market has been in telecommunications. The high reliability constraints and cost associated with fabrication of small volumes have hindered the standardization of fabrication process compared to CMOS. Furthermore, intellectual property issues complicate the widespread standard application of several key processes, including the growth of epitaxial layers.

One target for InP photonic integration is tunable DFB devices for dense division multiplexing systems. Several device designs are currently in production. For wide tuning ranges, vernier-type tuning has proven to be the most effective. In this approach, two grating patterns are slowly mapped onto each other to pick out a single wavelength for emission. One concern is the loss (absorption) in the cavity. Hence several monolithic devices include an amplifier or gain section in the device. Figure 93 shows an example of a single-chip monolithic device.

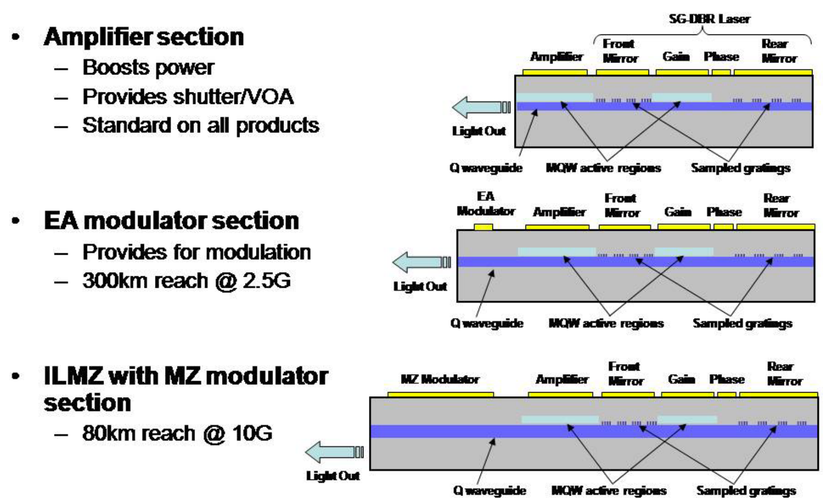


Figure 93: Monolithic Tunable Laser Device With or Without Modulator Section

Source: JDSU

It is difficult to integrate the InP device with the electronic control functions. Today, the process capabilities of InP electronics remain many years behind those of CMOS electronics. As a result, optoelectronic integrated circuits require separate electronic chips connected by wire bonds or flip chip technology. Figure 94 illustrates an example of the tunable laser chip for telecom applications with wire bond pad layout. Multiple pads are

required to control the different section of the chips. The semiconductor optical amplifier section and the laser gain section both require large current supplies.

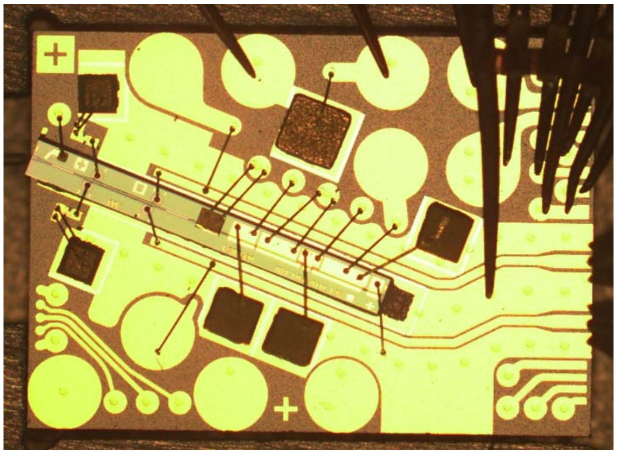


Figure 94: Pad Layout for a Tunable Device with Multiple Contact Pads for Wire Bonding
Source: JDSU

The tunable integrated devices are well understood in terms of performance and control. Mach Zender devices are very useful for new long haul systems because they make it possible to integrate coding functions on the same mask layout.

The advantage of the InP optoelectronic integrated circuit is the light source. The laser can be integrated into the circuit at the base wafer epitaxial growth stage. This approach makes it possible to fold most of the routing and detection emission functions into the first wafer processing stage. Waveguide integration is part of the epitaxial stage, using mode converted or couple waveguide solutions to route the light from the emitter into the waveguide path. Alternative ideas include using silicon dioxide waveguides deposited on the wafer during the fabrication processes. Defect formation, morphology control and doping control of the waveguide/laser/detector, and design setup are the key issues concerning the epitaxial growth.

The epitaxial device integration approach requires careful design of the chip layout. The key issues are feedback into the laser, noise control from spontaneous emission for the photodetector, and electrical pad layout. CAD tools for design and integration are available, but the tool sets are inferior to those available for CMOS electronics.

Several companies have been developing photonic integrated circuits for switching systems for telecom applications. The biggest issue with telecom applications is the reliability of the system. Carriers expect photonic ICs to deliver 25 years of service before replacement.

D-WDM systems are targets for photonic integration because of the requirements for tight wavelength spacing, cost, and wavelength control. Infinera has been developing devices for their D-WDM switches using photonic integrated circuits based on InP technol-

ogy. Their approach is to integrate multiple transmitters and receiver on the same piece of InP, as shown in Figure 95.

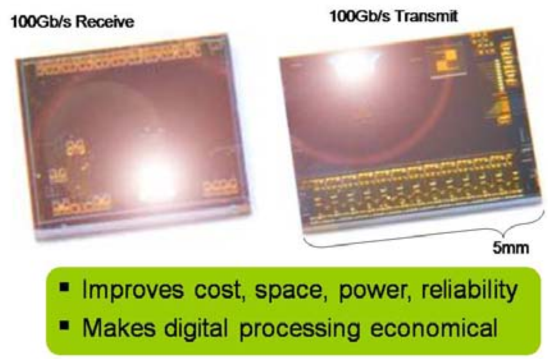


Figure 95: 100 Gbit Receive and Transmit Integrated Optic Devices for D-WDM Systems

Source: Infinera

A key figure of merit for the reliability of a device or component is the failures in time (FIT) rate. To qualify for communication networks, integrated circuits must meet Telcordia GR-468 standards. Figure 96 shows an example of the FIT rate that is achievable for optoelectronic integrated circuits.

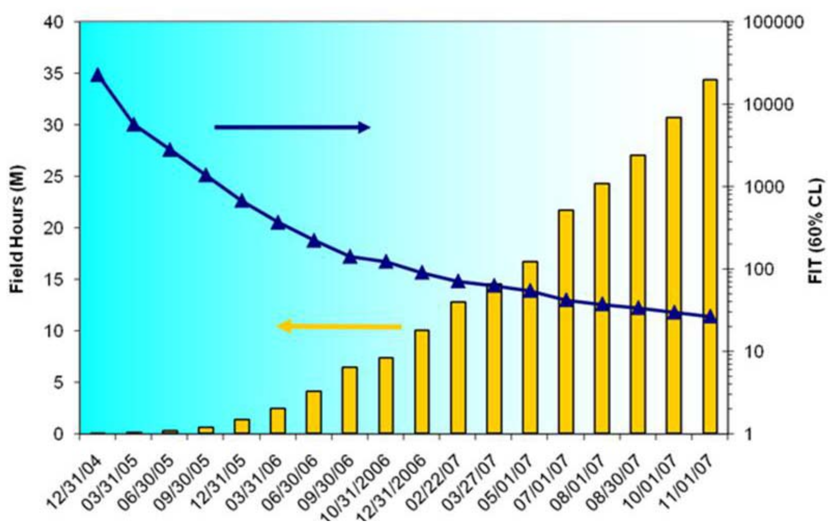


Figure 96: Photonic Integrated Circuit (PIC) FIT Rate with Field Deployment

Source: Infinera

This example of the FIT rate reaching nearly 10 FITs after three years of field deployment is a key milestone for InP photonic integrated circuits. It shows that integration can achieve comparable reliability to single component devices. The main concerns moving forward are increasing yield and increasing functionality.

D-WDM systems require high channel counts and high modulation speeds. One approach to meeting these requirements is to add more functionality into the current OEICs and increase the number of integrated sources. Currently research is ongoing to improve the density of channels and to increase the modulation bandwidth of the transmitter and receiver components. Figure 97 illustrates the current state of progress.

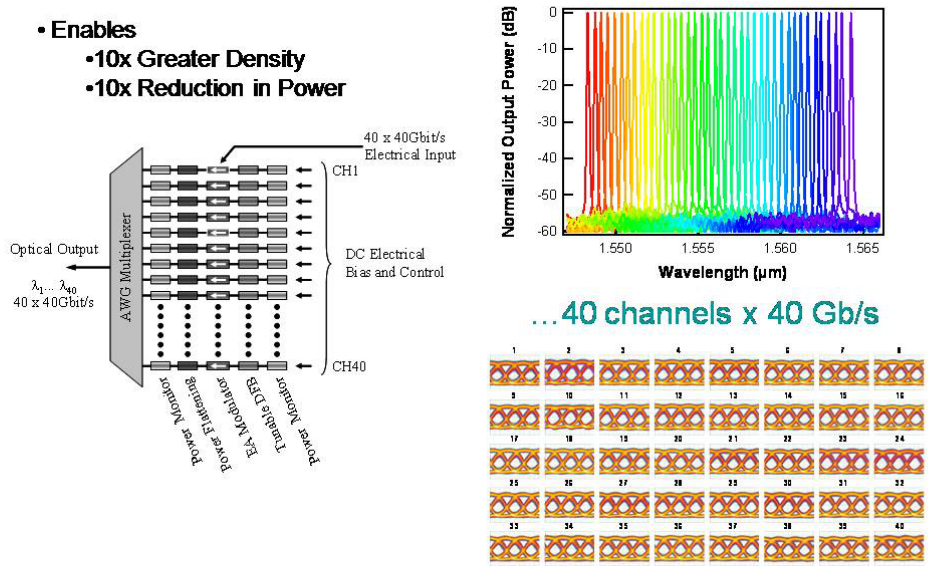


Figure 97: Wavelength Density and Modulation Capabilities of the PIC

Source: Infinera

Higher levels of integration make it possible to reduce power consumption. As new modulation formats increase the single wavelength information carrying capacity, integration of different components can enable greater fiber bandwidth.

Photonic integration research has been ongoing for nearly 20 years. The applications have targeted primarily the telecommunication industry. With the recent advances in both CMOS photonics for computer interconnects and InP integration for long haul systems, the future is bright for continued advances in this field.

10 Appendices

10.1 Acronyms and Abbreviations

ADM – Add/Drop Multiplexer

ADSL – Asymmetric Digital Subscriber Line

APD – Avalanche Photodiode

AWG – Arrayed Waveguide Gratings

BER – Bit Error Rate

BMR – Burst-Mode Receiver

BPON – Broadband Passive Optical Network

BTV – Broadcast Television

CAD – Computer Aided Design

CAGR – Compound Annual Growth Rate

CAPEX – Capital Expenditures

CATV – Advanced Cable Television

CD – Chromatic Dispersion

CDMA – Code Division Multiple Access

CDR – Clock and Data Recovery

CMOS – Complementary Metal Oxide Semiconductor

CO – Central Office

CSMA/CD – Carrier Sensed Multiple Access/Collision Detection

CWDM – Coarse Wavelength Division Multiplexer

DFB – Distributed Feedback

DQPSK – Differential Quadrature Phase Shift Keying

DSL – Digital Subscriber Line

DSP – Digital Signal Processor

DWDM – Dense Wavelength Division Multiplexing

EDFA – Erbium Doped Fiber Amplifiers

E-LAN – Ethernet Large Area Network

EML – Electro-absorption Modulation Laser

EP2P – Ethernet Point to Point

EPON – Ethernet Passive Optical Network

FFT – Fast Fourier Transform

FiOS – Fiber Optic Service

FIT – Failures in Time

FTTH – Fiber to the Home

FTTx – Fiber to the x

GEPON – Gigabit Ethernet Passive Optical Network

GFP – Generic Framing Procedure

GPLS – Globally Pseudochronous Locally Synchronous

GPON – Gigabit Passive Optical Network

GSM – Global System for Mobile Communications

HD – High Definition

HDTV – High-Definition Television

HUB – Video Hub Server

IEEE – Institute of Electrical and Electronic Engineers

IETF – Internet Engineering Task Force

IMS – IP Multimedia Subsystems

IP – Internet Protocol

IPO – Initial Public Offer(ing)

IPTV – Internet Protocol Television

ISDN – Integrated Services Digital Network

ISO – International Standards Organization

ITU – International Telecommunications Union

LAN – Local Area Network

LH – Long Haul

LLC – Logic Link Control

LRM – Long Reach Multimode

MAC – Media Access Control

MAN – Metropolitan Area Network

MBE – Molecular Beam Epitaxy

MEF – Metro Ethernet Forum

MMF – Multi-Mode Fiber

MMI – Multi-Mode Interference Couplers

MOCVD – Metallo Organic Chemical vapor Deposition

MOST – Media Oriented Systems Transport

MPLS – Multiprotocol Label Switching

MSA – Multiple Source Agreement

MSO – Multiple System Operator

M-Z – Mach Zender

NGN – Next Generation Network

NRZ – Non-Return to Zero

NRZ-OOK – Non-Return to Zero On-Off Key

OADM – Optical Add-Drop Modulator

OC-OFDM – Orthogonal Frequency-Division Multiplexing

OCS – Optical Core Switch

OED – Optical Edge Device

OEIC – Opto-Electronic Integrated Circuit

OEM – Original Equipment Manufacturer

OEO – Optical-Electrical-Optical

OIF – Optical Internetworking Forum

OLT – Optical Line Terminal

ONT – Optical Network Terminal

ONU – Optical Network Unit

OPEX – Operating Expenditure

OSI – Open Systems Interconnection

OSNR – Optical Signal to Noise Ratio

OTN – Optical Transport Network

PBBT – Provider Backbone Bridging Transport

PBT – Provider Backbone Transport

PIC – Photonic Integrated Circuit

PLC – Planar Light Circuit

PMD – Polarization Mode Dispersion

POF – Plastic Optical Fiber

PON – Passive Optical Network

QoE – Quality of Experience

QoS – Quality of Service

QPSK – Quadrature Phase Shift Keying

RBOC – Regional Bell Operating Company

ROADM – Reconfigurable Optical Add Drop Multiplexers

RSOA – Reflective Semiconductor Optical Amplifier

SAP – Service Access Point

SCH – Separate Confinement Heterostructure

SDH – Synchronous Digital Hierarchy

SFF – Small Form Factor Transceiver

SLA – Service Level Agreement

SOA – Semiconductor Optical Amplifier

SONET – Synchronous Optical Networking

TDM – Time Division Multiplexing

TDMA – Time Division Multiplexing Access

TIA – Telecom Industry Association

T-MPLS – Transport Multiple Protocol Label Switching

TO-can – Transistor Outline-can

UMTS – Universe Mobile Telecommunications Systems

VHO – Video Head-End Office

VOD – Video on Demand

VoIP – Voice over Internet Protocol

WAN – Wide Area Network

WDM – Wavelength Division Multiplexing

10.2 Forum Agenda

Future Optical Communication Systems
November 7- 8th, 2007 – Baltimore, MD

Day One - Wednesday 7th November

7.30 – 8.00 a.m.	Registration and Continental Breakfast
8.00 – 8.30	**Keynote: Business and Market Trends**
8.00 – 8.30	Goldman Sachs – *Jason Rowe*
8.30 – 9.40	**Core and Metro: Service Provider Perspectives**
Moderator: Fred Leonberger	
8.30 – 8.55 a.m.	Verizon – *Stuart Elby*
8.55 – 9.20	AT&T – *Mark Feuer*
9.20 – 9.40	Discussion Panel
9.40 – 10.00	**Coffee Break**
10.00 – 12.15	**Core and Metro**
Moderator: Bill Ring	
10.00 – 10.20	Calient – *Jonathan Lacey*
10.20 – 10.40	Infinera – *Dave Welch*
10.40 – 11.00	Mintera – *Niall Robinson*
11.00 – 11.20	UC Davis – *S.J. Ben Yoo*
11.20 – 11.40	Xtera – *Trent Coroy*
11.40 – 11.55	Moderated Discussion
11.55 – 1.10	**Lunch**
1.10 – 3.10	**Technology and Devices Part 1**
Moderator: Fred Leonberger	
1.10 – 1.30	Corning – *Luis Zenteno*
1.30 – 1.50	JDSU – *Ed Murphy*
1.50 – 2.10	Bookham Technologies – *Chris Clarke*
2.10 – 2.30	Avanex – *Giovanni Barbarossa*
2.30 – 2.50	UCSB – *Larry Coldren*
2.50 – 3.10	Opnext – *Ed Cornejo*
3.10 – 3.30	Finisar – *Julie Eng*
3.30 – 3.50	Moderated Discussion
3.50 – 5.50	**Break and Breakout Discussion**
3.50 – 4.05	**Organize Breakout Sessions & Coffee Break**
4.05 – 5.35	Breakout Discussions
5.35 – 5.50	Reports from Breakout Leaders
6.00 – 8.00	**Evening Networking Reception**

Day Two - Thursday 8th November

8.00 – 8.30 am	Registration and Continental Breakfast

8.30 – 9.00	**Keynote: Business and Market Trends**
8.30 – 9.00	Ovum – *Karen Liu*
9.00 – 11.30	**Access and Metro**
Moderator: Bill Ring	
9.00 – 9.20	Cisco Systems – *Adam Carter*
9.20 – 9.40	Alcatel-Lucent – *Marcus Duelk*
9.40 – 10.00	Anda Networks – *Greg Gum*
10.00 – 10.20	Telcordia Technologies – *Ron Menendez*
10.20 – 10.40	Motorola – *William Weeks*
10.40 – 11.00	OptiComp – *Peter Guilfoyle*
11.00 – 11.30	Moderated Discussion
11.30 – 12.15	**Lunch**

12.15 – 2.15	**Technology and Devices Part 2**
Moderator: Fred Leonberger	
12.15 – 12.35	MIT – *Rajeev Ram*
12.35 – 12.55	Alphion – *Leo Spiekman*
12.55 – 1.15	CyOptics – *Stefan Rochus*
1.15 – 1.35	Intel – *Andrew Alduino*
1.35 – 1.55	CeLight – *Isaac Shpantzer*
1.55 – 2.15	Moderated Discussion
2.15 pm	Adjourn

Concurrent Post Forum Meetings

2.30 – 5.00 p.m. **Silicon Photonics Alliance Meeting**

Membership is not required to attend this meeting. More information regarding the OIDA Silicon Photonics Alliance (SPA) can be found at: http://www.oida.org/spa.

2.30 – 5.00 p.m. **OIDA Steering Committee Meeting (by invitation)**

Key topics include:

- 100 G Study (DARPA-Sponsored)
- Virtual Photonics Foundry Update
- Annual Forum Planning